RESTART

(MAY 2022– APRIL 2025)

REcycling of Spent Li-ion baTteries and end-life photovoltAic panels: from the development of metal Recovery processes to the implementation of a sTart-up

LEAP-RE

Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy

Pillar-1 project

The LEAP-RE project has received funding from the European Union's Horizon 2020 Research and Innovation Program under Grant Agreement 963530.

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Consortium

The partners were selected considering the complementarity of their expertise and the international multidisciplinary to achieve the objectives of the project

Project coordinator:

- I. Saadoune, Cadi Ayyad University (UCA), **Morocco**

Project partners:

- Aalto University (**Finland**),
- Centre Européen de Recherche et d'Enseignement en Géosciences de l'Environnement - CEREGE (**France**),
- Mohammed VI Polytechnic University - UM6P, and Green Energy Park (**Morocco**),
- Babeș-Bolyai University (**Romania**)
- King Salman International University (**Egypt**)

Aim of the project

The main objective of RESTART Project is to implement a full value chain for recycling End-of-Life (EoL) LiBs and PV, shifting from linear economy to circular economy, thus reducing waste disposal as well as minimizing dependence on critical minerals. The specific objectives are : **Collect ; Recycle ; Implement; Coordinate.**

The targeted metals: Co, Ni, Li, Mn are considered as strategic ones for the deployment of an effective energy transition

Relevance vs MARs

RESTART project's deliverables are in accordance with the following outcomes and impacts of MAR 2:

- **Map of the EoL/OoS component value chain**
- **Proposal of methods for EoL/OoS component recycling**
- **Identification of second life components with a benefit for African countries**
- **Dissemination of acquired knowledge**
- **Creation of jobs**
- **Promotion of environmental and ecological sustainability**

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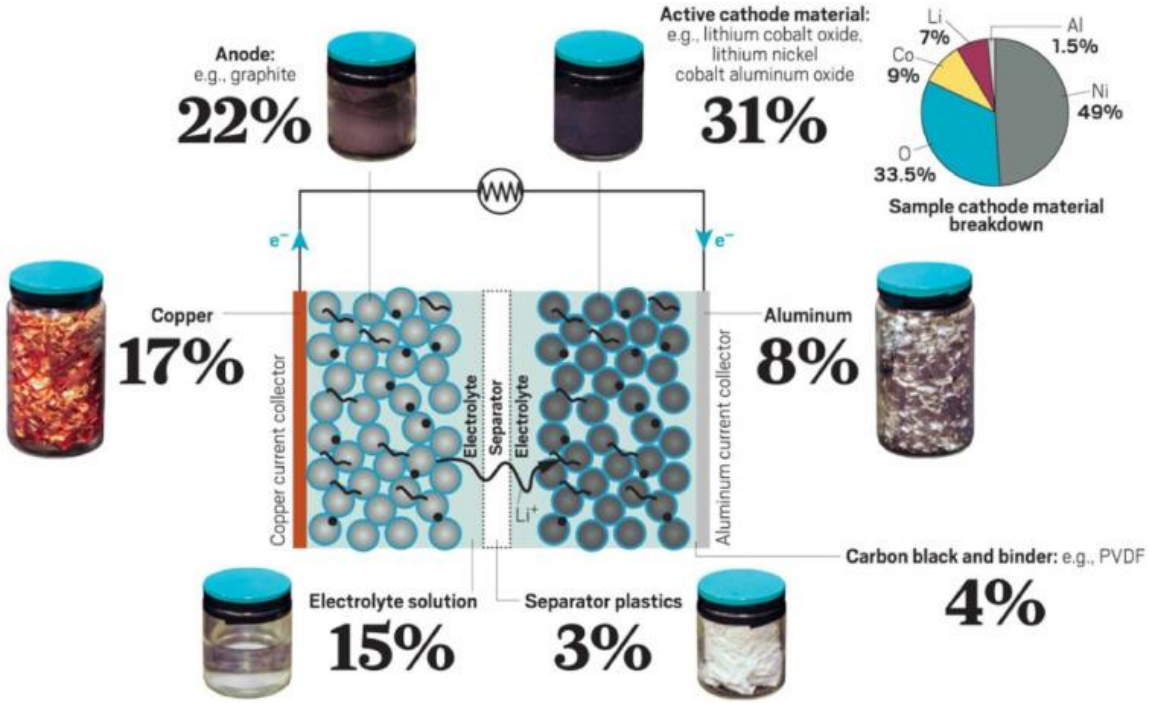

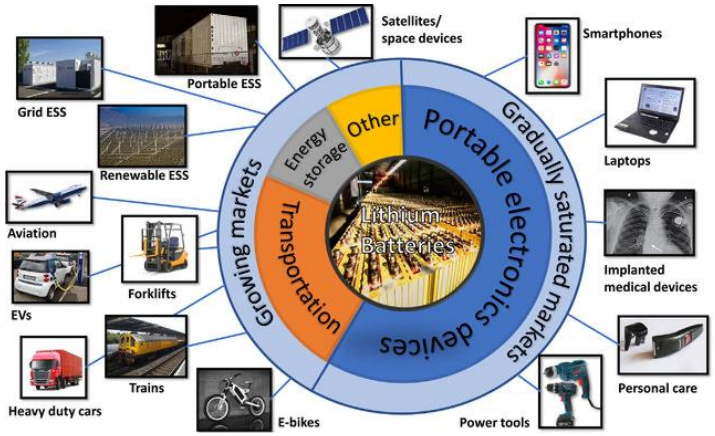

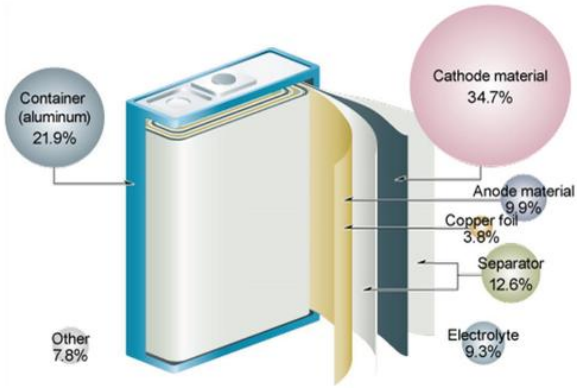

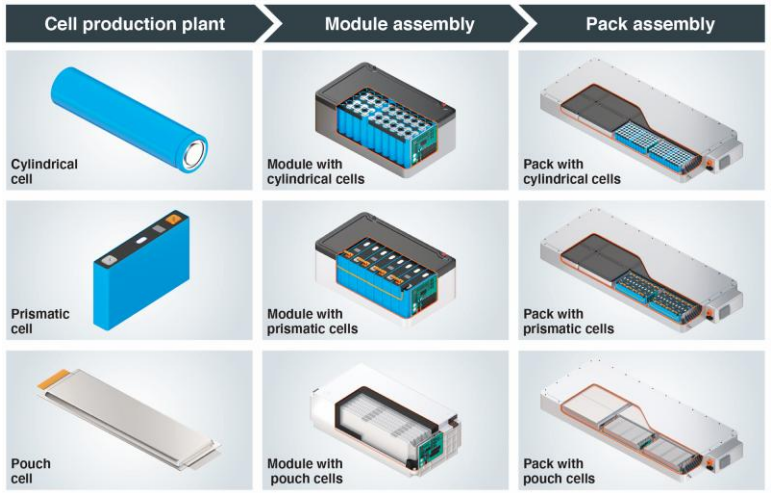

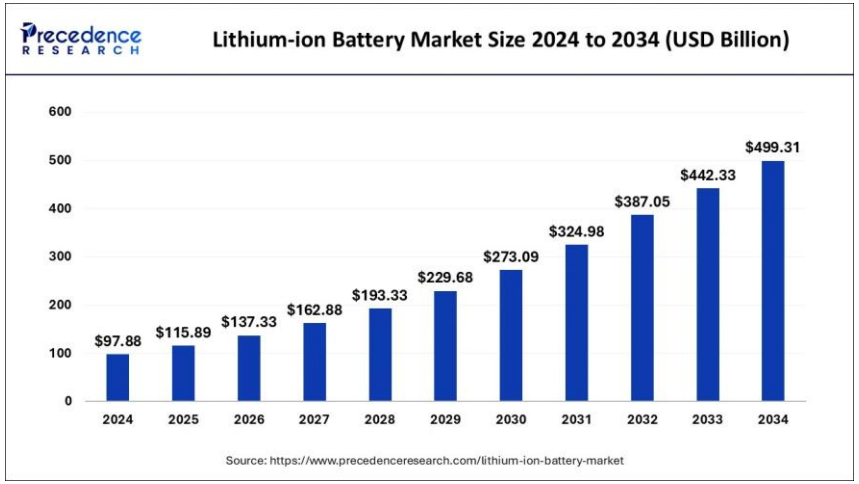

1. **REDUCING THE ENVIRONMENTAL IMPACT** (Groundwater ; Refining Process (Mining))
2. **ECONOMIC OPPORTUNITY**

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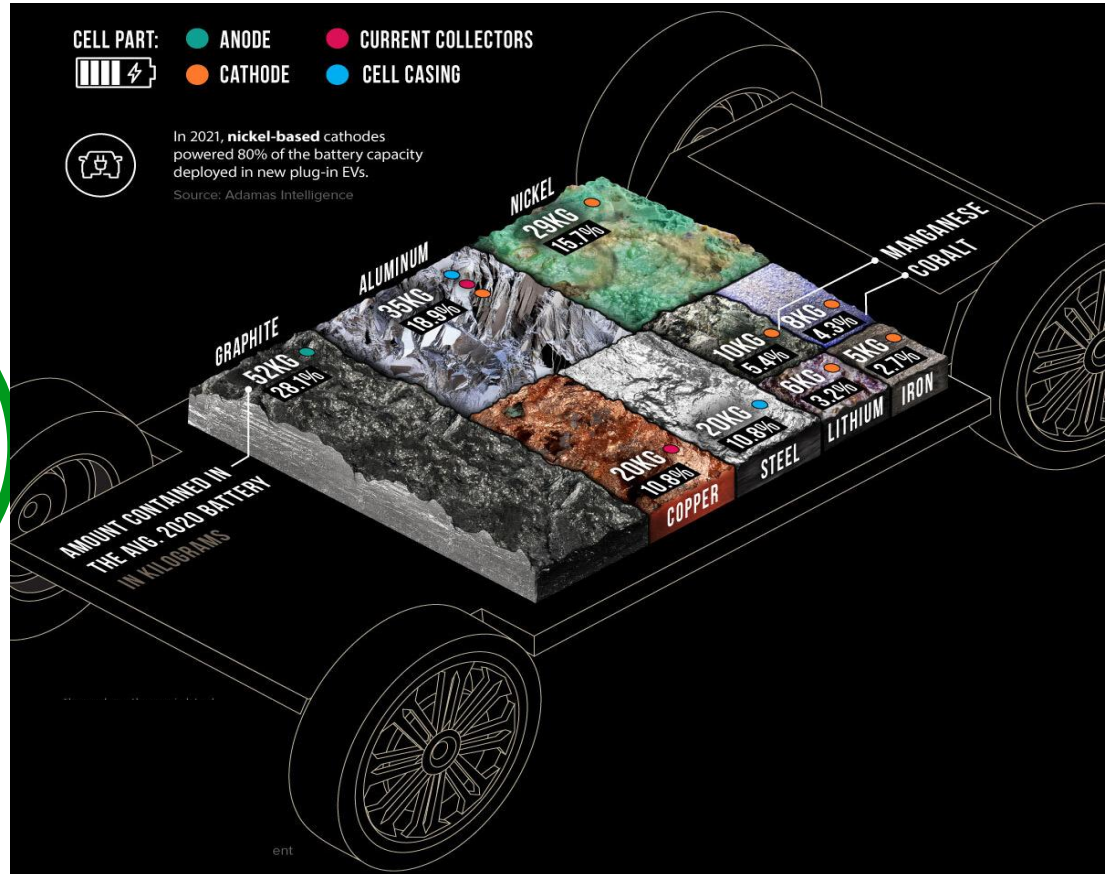
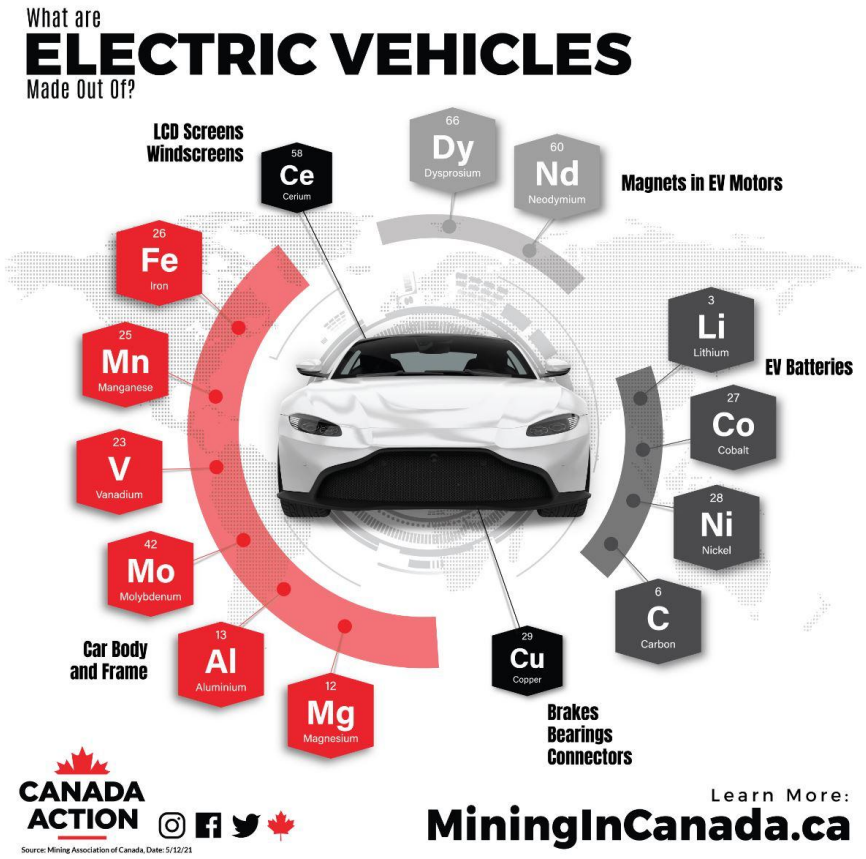
Key Minerals in an EV Battery for instance





- **Lithium-ion Batteries harness the properties of various minerals to power electric vehicles**
- **The cells in the average LiB Battery with a 60 KWh capacity contain around 185 Kg of Minerals (without considering the chemicals existing in binder, electrolyte, separator and pack casing**

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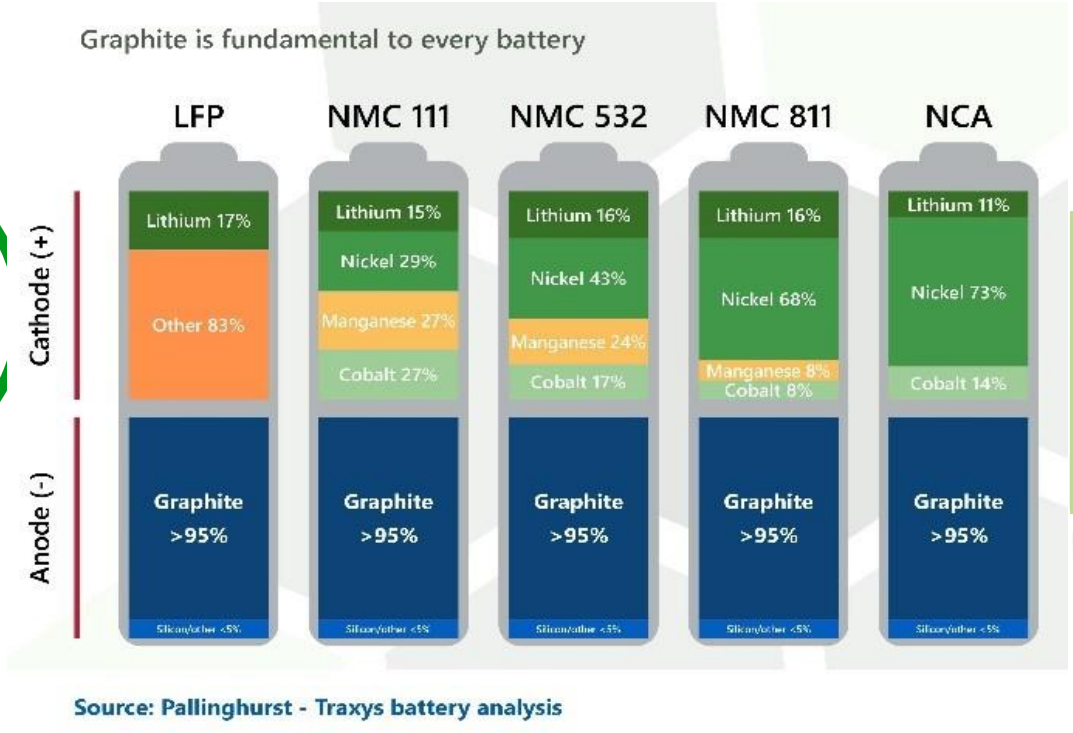
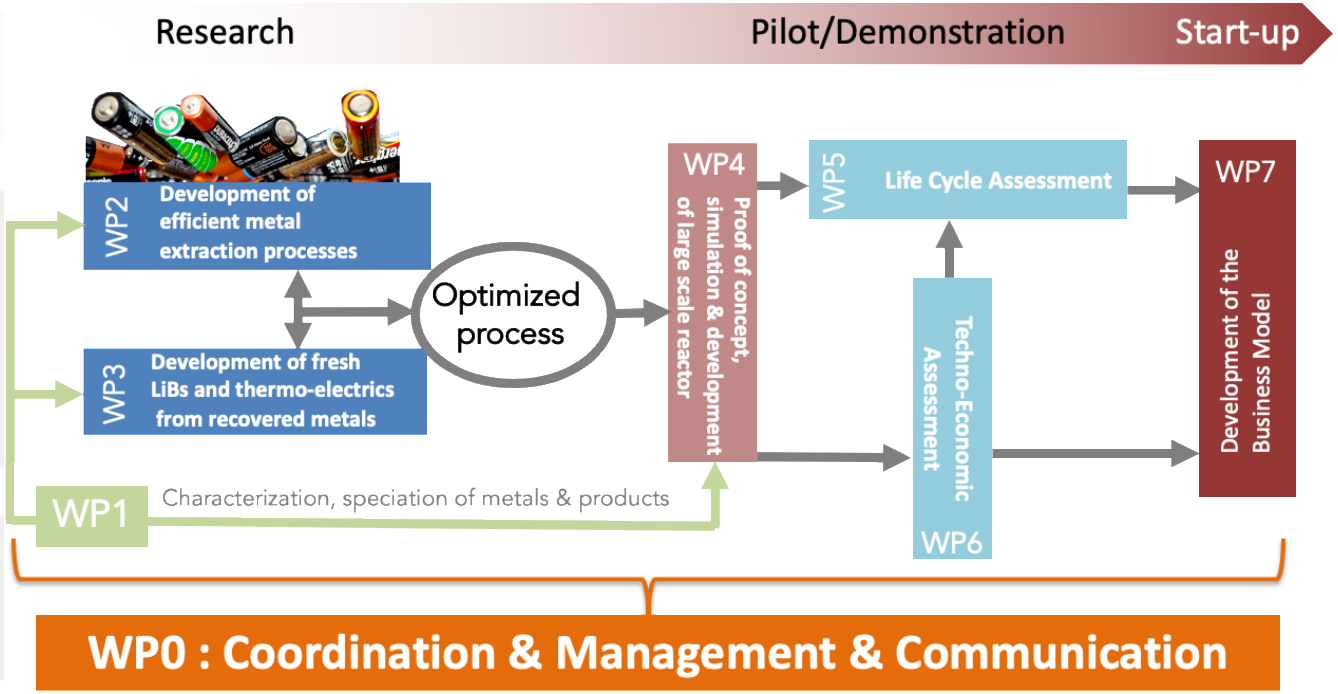
COMMERCIALIZED Li-ion BATTERIES





RESTART Project is to implement a full value chain for recycling (EoL) LiBs and PV covering all aspects including: Technology; Sustainability and Economic

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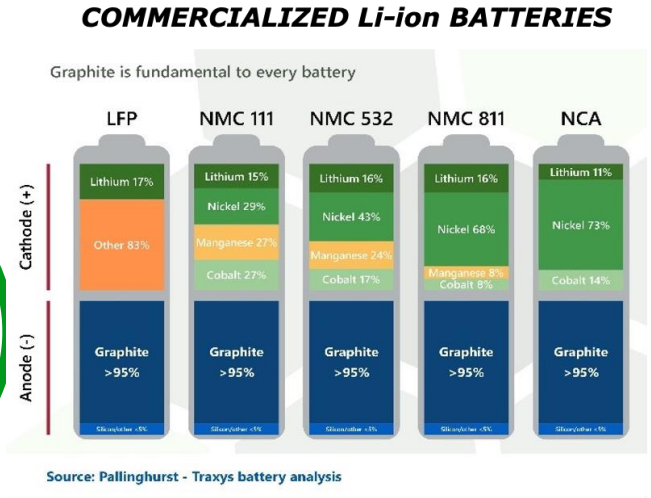
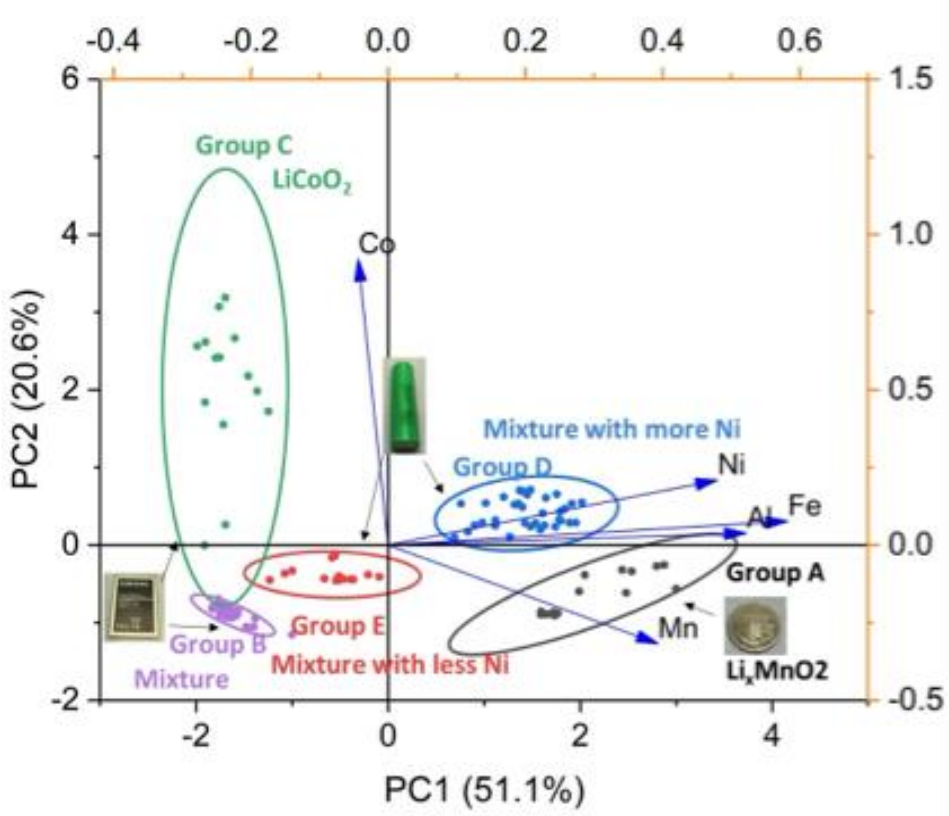
First Step : Determining the Composition and Chemical Forms of Elements in End-of-Life Batteries





A Rapid Method to Identify the Cathode Type of End-of-Life Lithium-Ion Batteries by X-ray Fluorescence Spectroscopy for Optimizing Battery Recycling

Revised version under review (2025): Communications Engineering

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Developed recycling processes for cathodes : Hydrometallurgy

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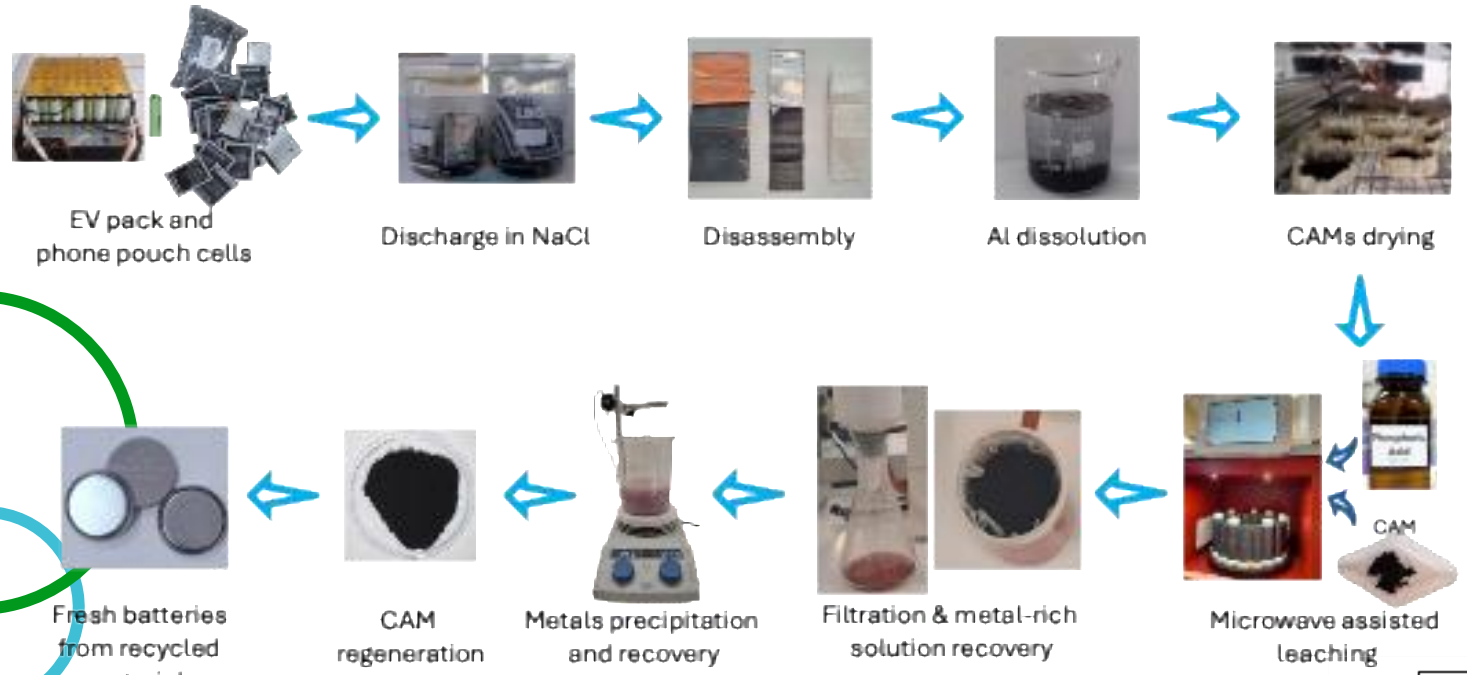


Journal of Power Sources 580 (2023) 233341

Contents lists available at ScienceDirect

Journal of Power Sources

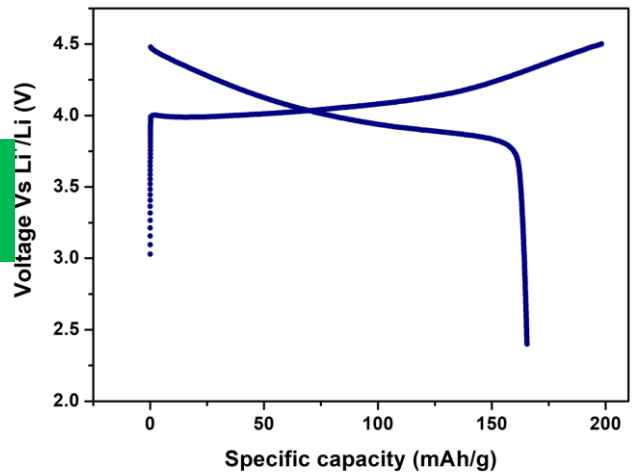
journal homepage: www.elsevier.com/locate/jpowsour

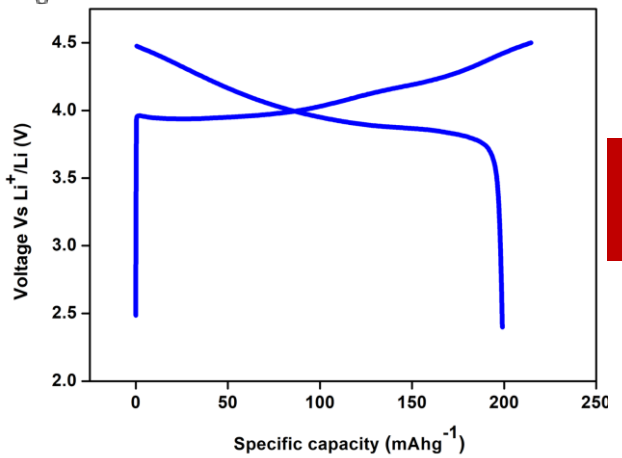
Towards a closed loop recycling process of end-of-life lithium-ion batteries: Recovery of critical metals and electrochemical performance evaluation of a regenerated $LiCoO_2$

Marouane Aannir [a,b,c], Rachid Hakkou [a,d], Clément Levard [b], Yassine Taha [d], Abdellatif Ghennioui [c], Jérôme Rose [b], Ismael Saadoune [d,*]

[a] Cadi Ayyad University (UCA), Faculté des Sciences et Techniques, IMED Laboratory, BP 549, Marrakech, 40000, Morocco
[b] Aix Marseille Univ, CNRS, IRD, INRAE, CEREGE, Aix-en-Provence, France
[c] Green Park Energy (GEP), Route Régionale Kelaa Km 3, R206, Ben Guerir, Morocco
[d] Mohammed VI Polytechnic University (UM6P) Lot 660, Hay Moulay Rachid, 43150, Ben Guerir, Morocco

Li-Battery from recycled metals





Li-Battery from purchased metals

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Developed recycling processes for cathodes : Molten Salt

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Materials Today Communications 36 (2023) 106603

Contents lists available at ScienceDirect

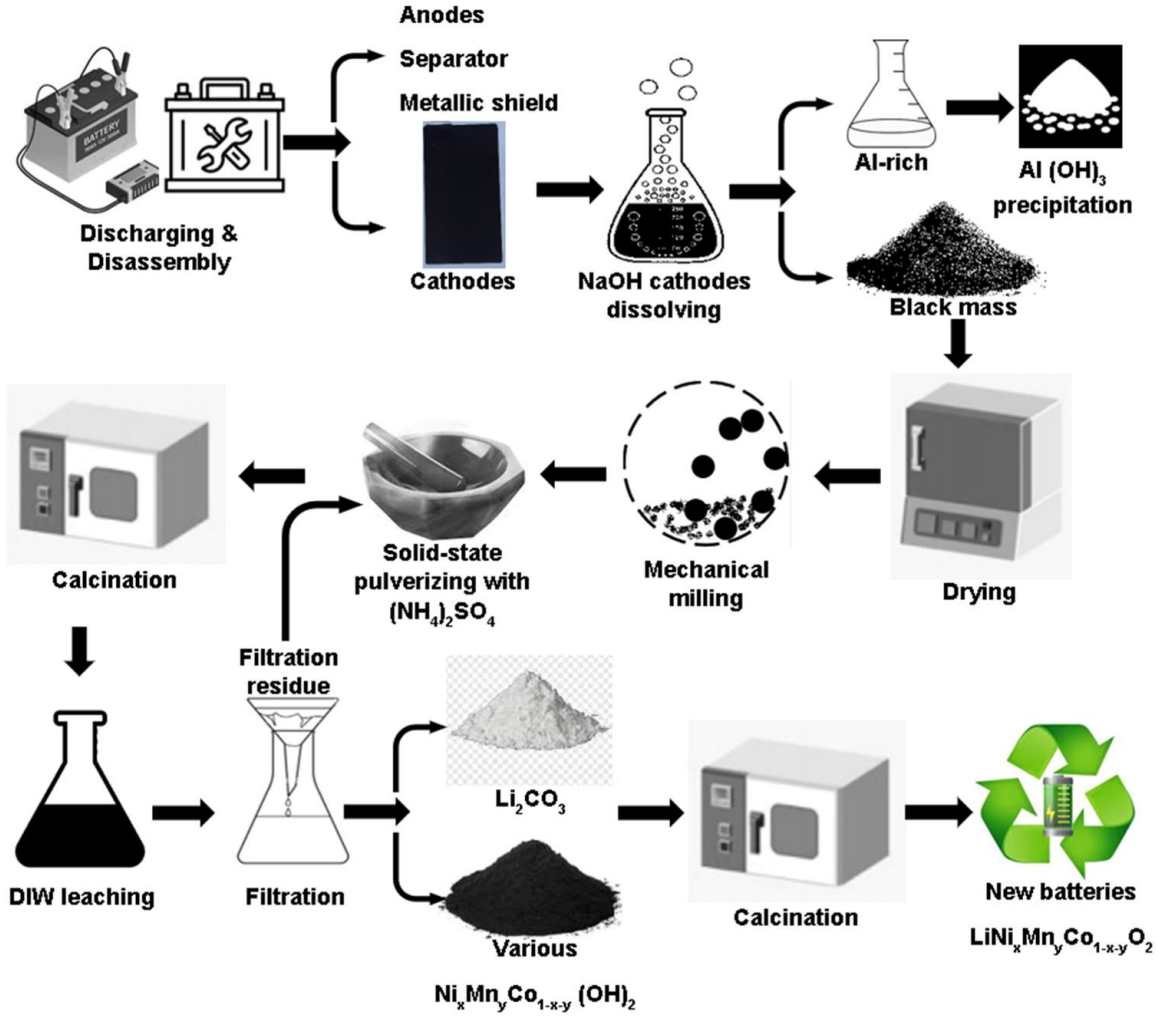
Materials Today Communications

journal homepage: www.elsevier.com/locate/mtcomm

Comparative performance analysis of NMC cathodes elaborated from recovered and commercial raw materials: A low-temperature molten salt approach for extracting critical metals from end-of-life lithium-ion batteries

Nabil El Mounafia [a,b], Marouane Aannir [a,b,c], Rachid Hakkou [a,d,*], Abdelghafour Zaabout [e], Ismael Saadoune [a,e]

[a] Cadi Ayyad University (UCA), Faculty of Sciences et Technologies, IMED Laboratory, BP 549, Marrakech 40000, Morocco
[b] Green Park Energy (GEP), Route Régionale Kelaa Km 3, R206 Ben Guerir, Morocco
[c] Aix Marseille Univ, CNRS, IRD, INRAE, CEREGE, Aix-en-Provence, France
[d] Mohammed VI Polytechnic University (UM6P), GSMI, Lot 660, Hay Moulay Rachid, 43150 Ben Guerir, Morocco
[e] Mohammed VI Polytechnic University (UM6P), ACER, Lot 660, Hay Moulay Rachid, 43150 Ben Guerir, Morocco



The leaching efficiencies reached 95.4%, 94.8%, 93.4%, and 92.6% for Li, Mn, Ni, and Co, respectively. The lithium carbonate obtained through ion-exchange exhibited a pure phase

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Developed recycling processes for cathodes : Microwave using Phosphoric Acid

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Patent draft

Abstract

A method is described for recycling lithium-ion batteries, involving disassembling the lithium-ion batteries into anodes, cathodes, separator, plastic case, and metallic case, and immersing the cathodic sheets in a sodium hydroxide aqueous solution. The filtrated battery residues are fed into a dryer. The dried residues are ground into fine particles, and mixed with an acid and reduction agent to form a slurry to leach metal oxides using microwave. The leachate is filtered to remove non-leachable metals and residue before being transferred to a precipitation tank. The leachate was brought to pH=6.3 to remove soluble aluminum contamination. Cobalt, nickel, and manganese were coprecipitated directly as hydroxide. Lithium was precipitated as lithium carbonate adding sodium carbonate to the remaining liquor and heating up. The precipitated hydroxide mixture of nickel, cobalt, and manganese and lithium carbonate were dried, ground together, and calcinated. The calcinated product was then used as cathodic active material.

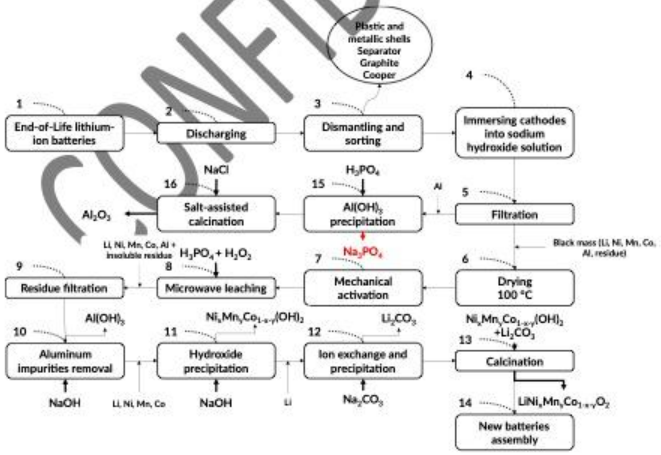
Technical field

[0001] It is provided a process for lithium-ion batteries.

Background

[0002] Recycling used lithium-ion batteries is an important aspect of managing the waste generated by these batteries, neutralizing the environmental impact of their production, and providing alternative sources of battery materials at affordable cost. Several recycling techniques were used, yet did not much the full requirements, either by presenting a significant environmental impact or not reaching the economic target by failing to recover many valuable metals.

[0003] Pyrometallurgical routes employ elevated temperatures to extract different elements from spent lithium-ion batteries, with anodic graphite and any organic components acting as the reducing agent and heat source. Heavier metals such as nickel, cobalt, and manganese are recovered as alloys and then further treated to do the separation. Lithium on the other hand is lost in the slag which decreases the overall economic of the processes.

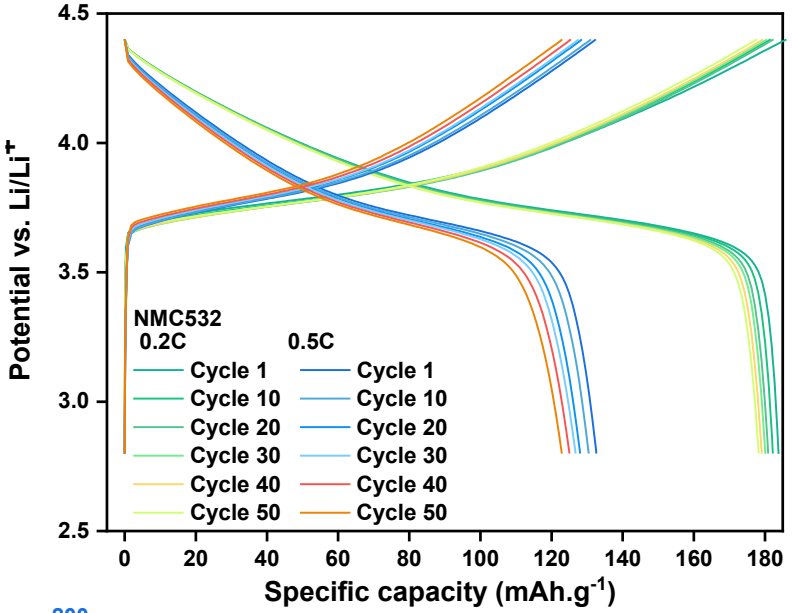


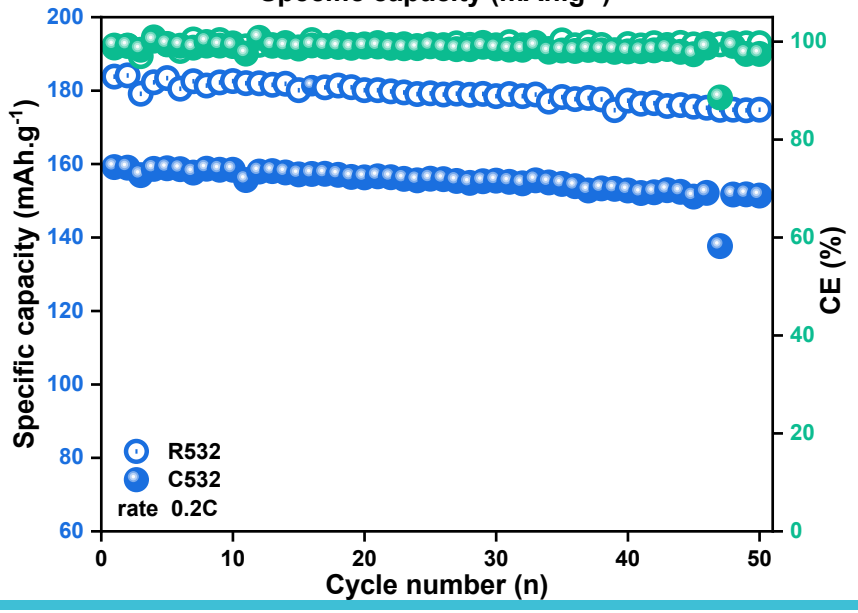
Patent submitted in collaboration with IRESEN

Regenerated products performance

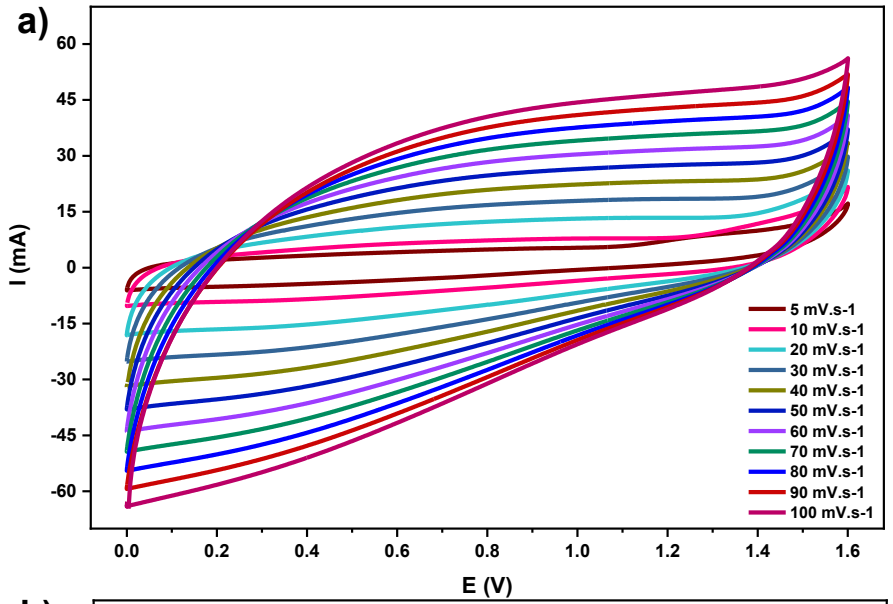
Cathodic materials:

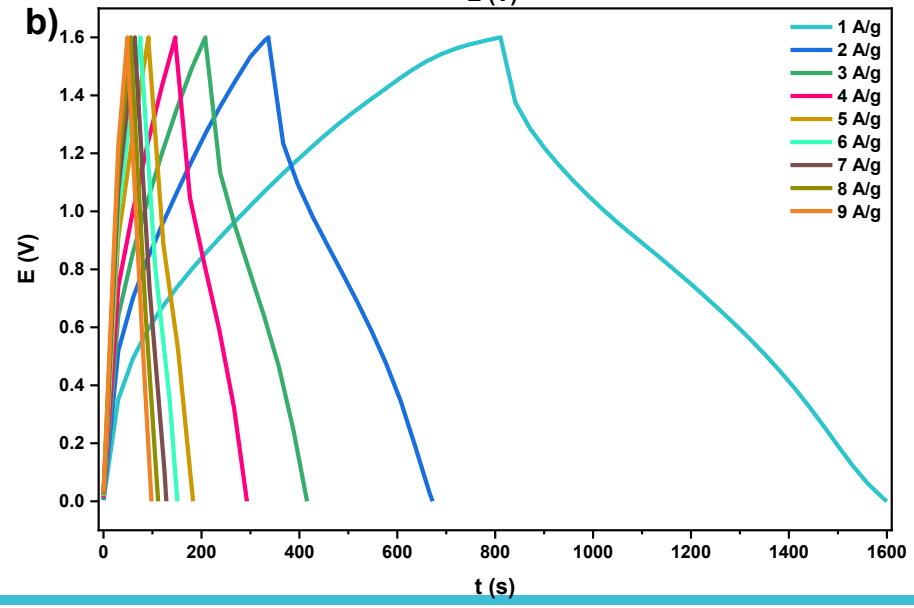
- *In Li-ion batteries*





- *In supercapacitors*





Techno-economic validation

Methodology: *process design and SEA tool*

Techno-economic process main steps

- **Mass & heat balance calculations** (via simulation or hand calculations and estimations)
- **Equipment choice**
- **Element Costs**
- **SEA tool**
- **Generation of economic results**

Standardized Economic Assessment Tool **(SEA)** is an Excel-based framework designed to conduct techno-economic assessments of chemical and energy processes. It integrates into the process development cycle, following steps such as concept development, process simulation, process design, and sustainability evaluation.

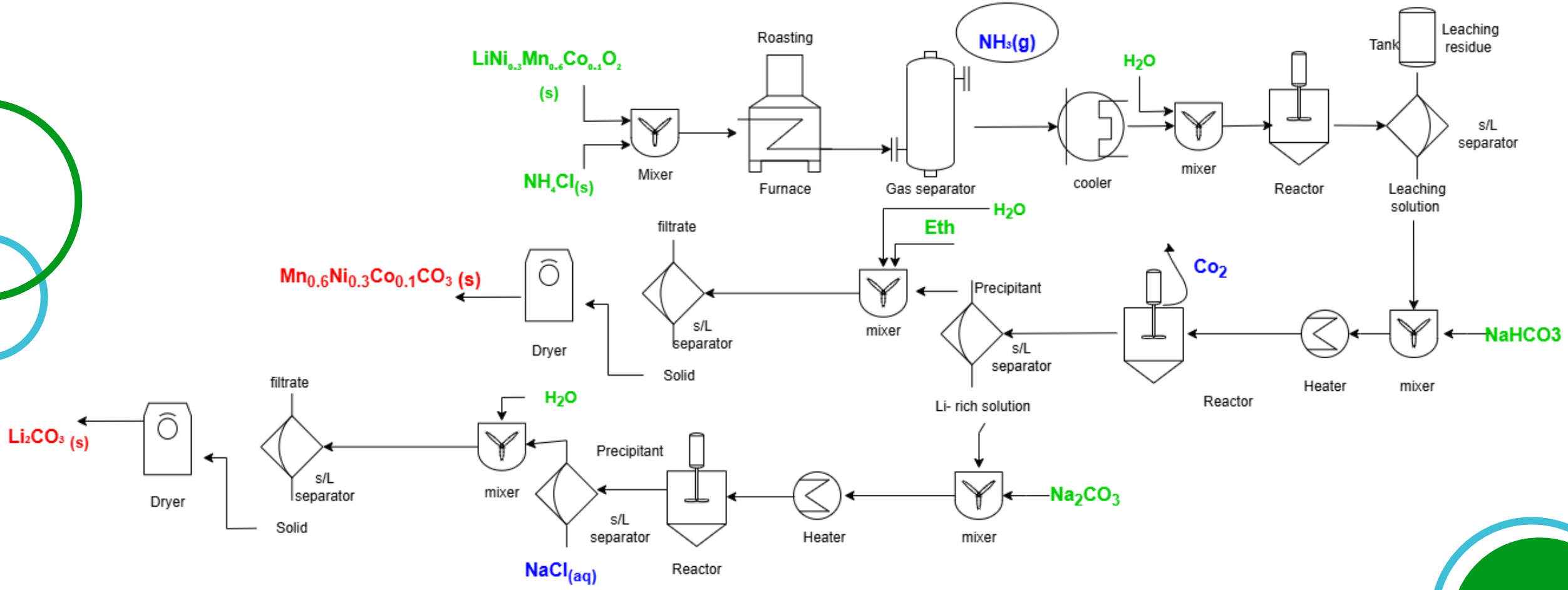
SEA helps to estimate:

- **Capital Costs (CAPEX)**
- **Operating Costs (OPEX)**
- **Levelized Cost of Product (LCOP)**
- **Payback Period, IRR, NPV**
- **Design decisions**
- **Benchmarking and sensitivity analysis.**

Techno-economic validation

Molten salts: *Applied on NMC*

Process design



Techno-economic validation

***Molten salts:* Applied on NMC**

Cash flow analysis

Economic Indicator	LCOP	
LCOP	3.822	$/kg
NPV	3.3	M$
IRR	8	%

LCOP: Levelized Cost of Product
NPV: Net Present Value
IRR: Internal Rate of Return

Economic Analysis Assumptions		Economic Analysis Input/Output	
Capacity Factor 1st year	25%	**Price of Product**	6.78 $/kg
Capacity Factor (remaining)	90%	**Discount rate**	8 %
Plant Lifetime	25 years	**Discounted Cash Flow**	3.269128109 M$
Construction period	3 years		

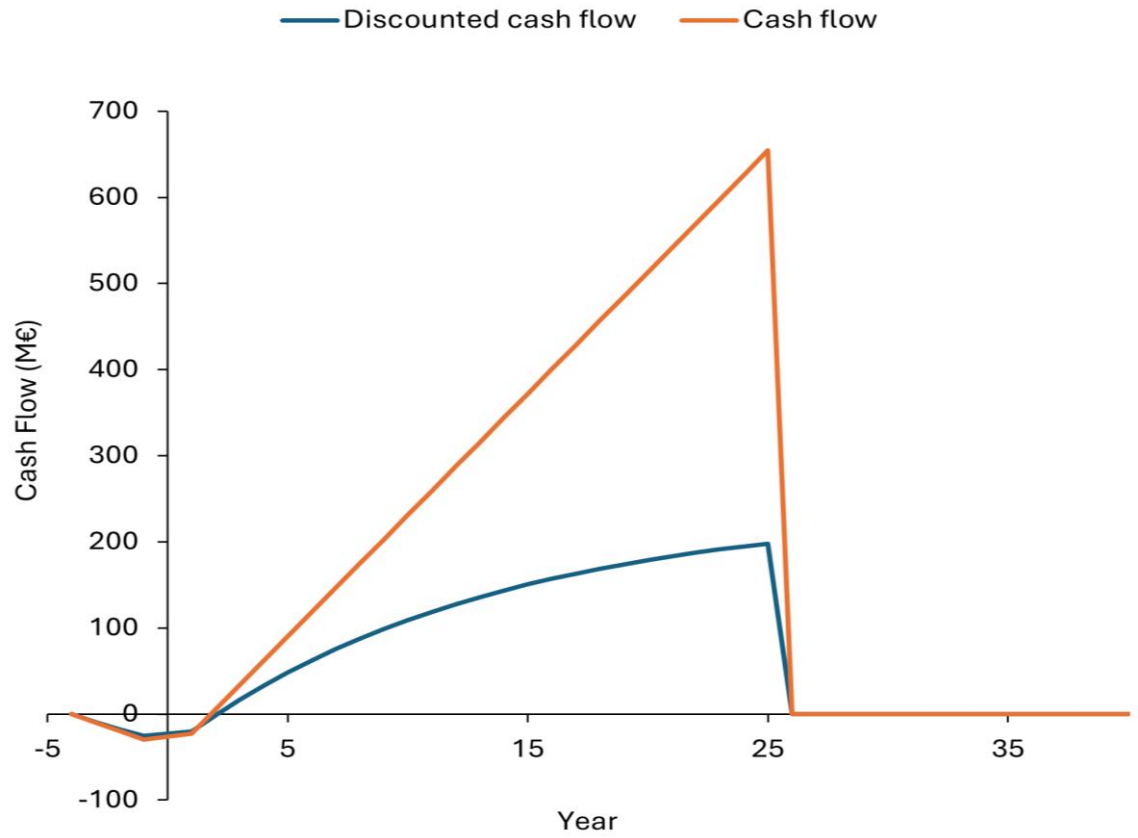


Figure 2. Cash Flow and Discounted Cash Flow Over 25-Year Project Lifetime

Developed recycling processes for anodes

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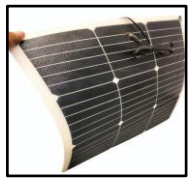
Si-Solar panels



Waste solar panel

- Disassembling
  - Backsheet
  - Junction box
  - Cables and electrodes
  - Encapsulation Layers

Physical & chemical separation

Filtration

Thermal pretreatment at 500°C

Milling: Particle size<120µm

Alkaline leaching (KOH)

Developed recycling processes for cathodes

Graphite recycling

Used batteries

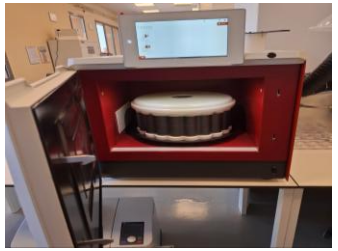
Discharge & disassembly

Physical separation

Delamination: ultrasound + water

Inert thermal pretreatment at 500°C

Milling & microwave treatment (H_2SO_4)

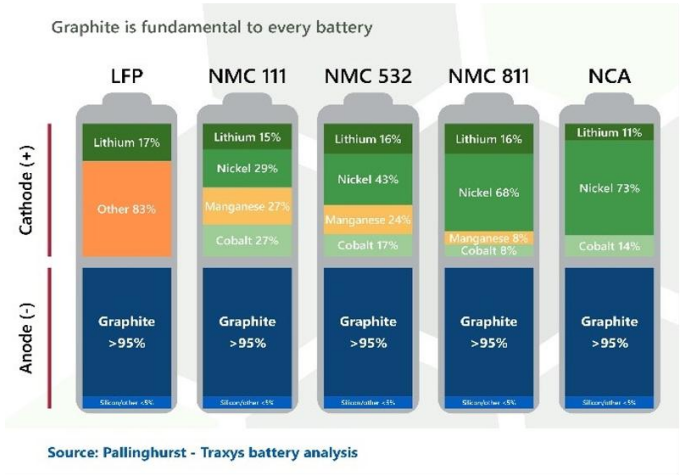


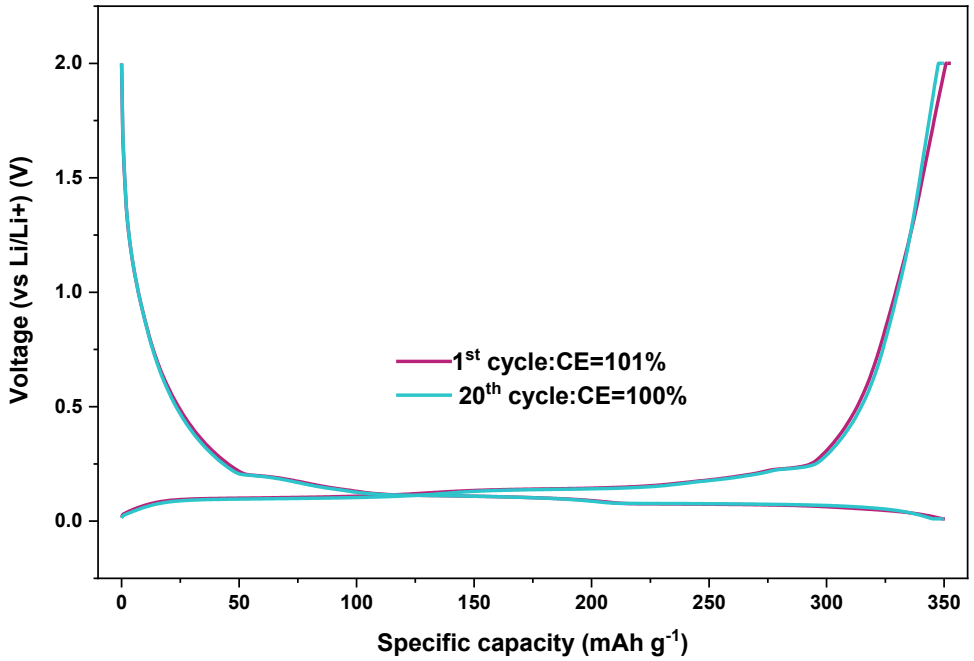
Fresh anode material: **Blended graphite/Si**

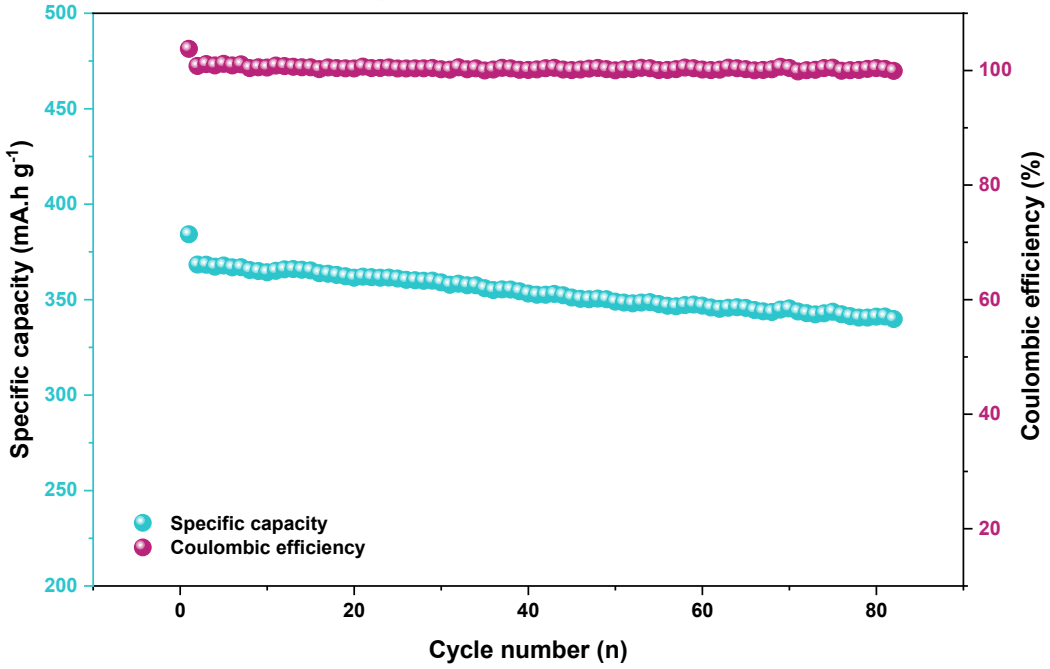
Regenerated products performance

Anodic materials: *Graphite/Si*

COMMERCIALIZED Li-ion BATTERIES







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Achievements

LEAP-RE

2 PhD Thesis : Dr AANNIR (UCA-CEREGE) ; Dr EL MOUNAFIA (UM6P-GEP-UCA) (Job Creation)

5 Master Thesis

07 Scientific Publications (Q1, I.F. > 5)

02 Patents

Two funded Projects : 1. RCLIB (LEAP RE) ; 2. Morrocan Company

UNESCO Chair : e-waste Recycling (Polytech Montréal)

THANK YOU

CONTACT US FOR MORE INFORMATION

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