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TECHNOLOGICAL
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SINGAPORE



E-waste Recycling

NTU-Singapore CEA Alliance for Research
in the Circular Economy (SCARCE)

*Prof. Madhavi Srinivasan (NTU)
Dr. Jean-Christophe Gabriel (CEA)*

14th Aug 2020

Financial support from NRF, NEA & MND, award #USS-IF-2018-4



E Waste

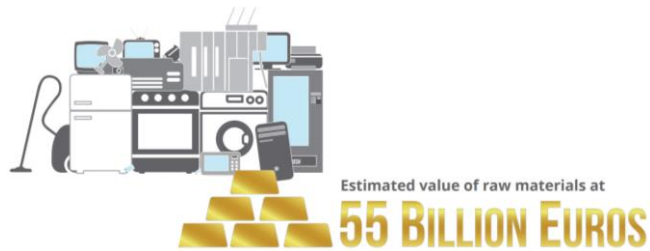
Worldwide 45 million tonnes of e-waste was generated in 2016



≈ 4500 Eiffel towers

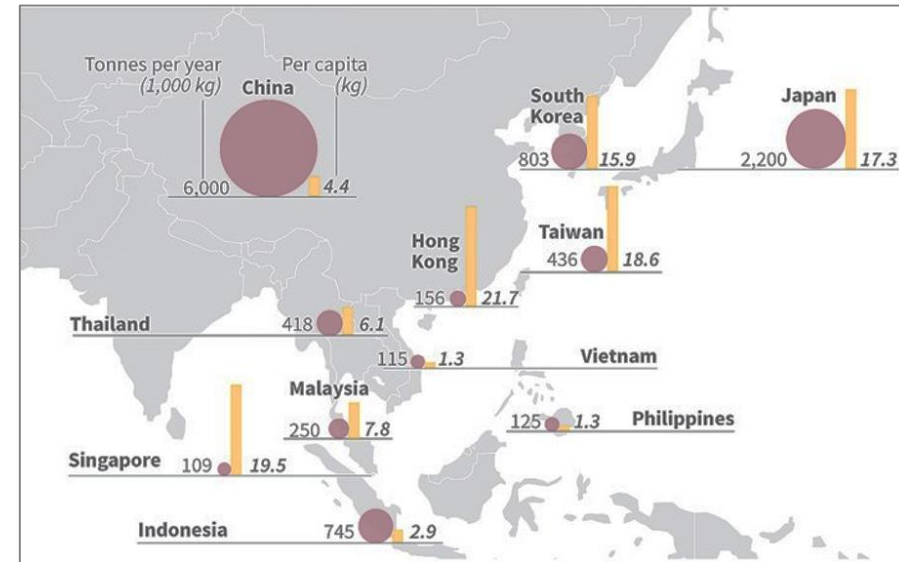
15-20% are recycled or “downcycled”

E-waste contains **toxic** elements, such as Pb, Cd, Hg, etc, poses health, environmental hazards



Up to 60 elements from the periodic table can be found in complex e-waste along with plastics and many of them are technically recoverable.

E-waste in Asia



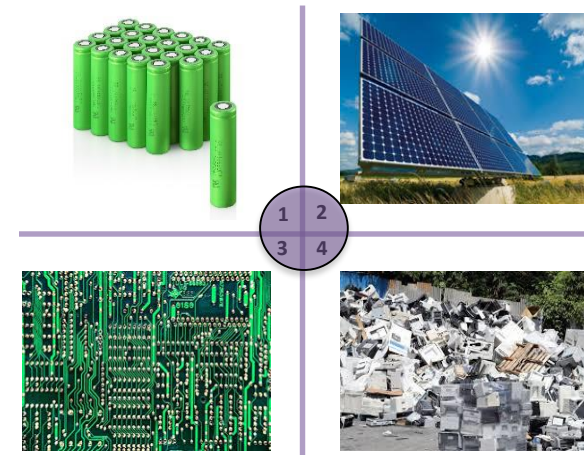
- In Singapore generates 60,000 tonnes of e-waste per year (NEA).
- Second largest producer of e-waste in this region 19.5 kg per person e-waste

Source : UNU-VIE Sustainable Cycles Programme/Japan Ministry of Environment

NTU Singapore – CEA Alliance for Research in Circular Economy (SCARCE)



- SCARCE aims to develop innovative, solutions for the recycling and recovery of resources from electrical and electronic waste (e-waste)
- SCARCE will focus on four research thrusts :
 - Thrust 1:** Recycling of advanced lithium ion batteries
 - Thrust 2:** Recycling of silicon solar panels
 - Thrust 3:** Recycling and recovery of valuable metals from printed circuit boards
 - Thrust 4:** Recycling and treatment of plastic part from e-waste



10 (NTU) + 12 (CEA)+ 30 (Researchers)
3 years



SCARCE Project Scope





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RT 1: Recycling of Lithium ion Batteries

Madhavi Srinivasan (NTU), Dalton Tay (NTU)
Daniel Meyer (CEA), Andreas Brambilla (CEA)

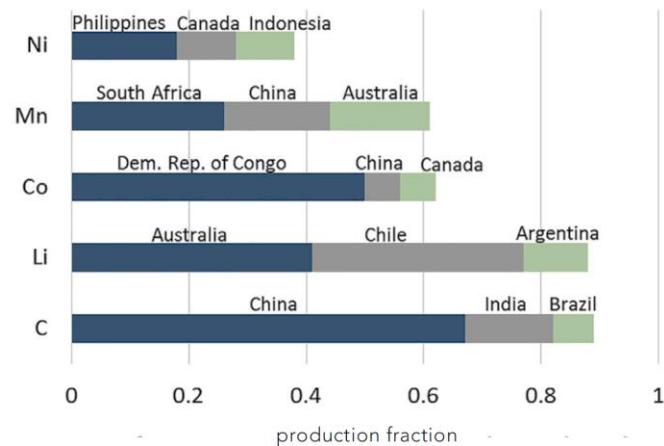


Why Recycle Lithium ion Batteries (LIB)?

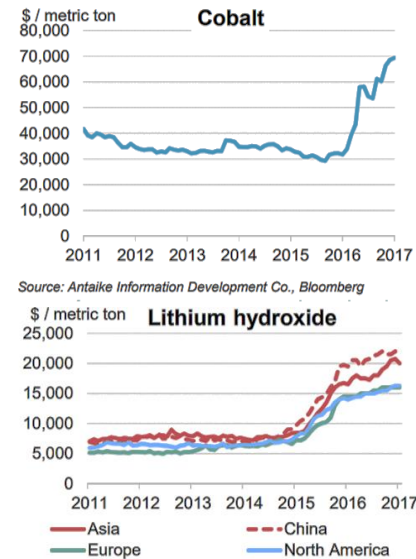
Environmental Concern

- Toxic Heavy metals like Co, Ni, and Mn would contaminate soil and water
- Corrosive hazardous gas such as hydrogen fluoride (HF), CO, CO₂, etc

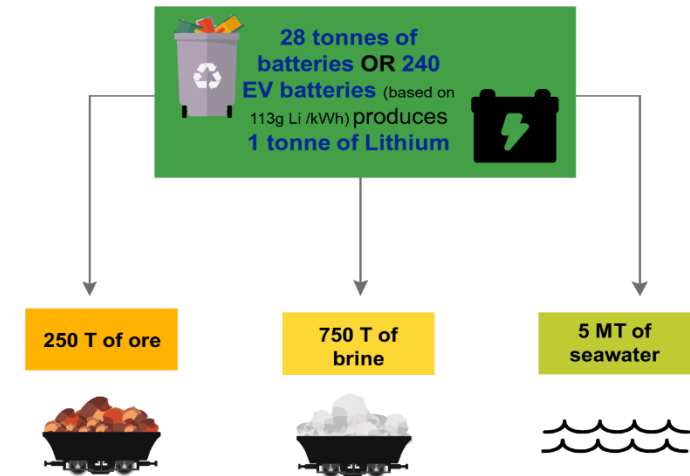
Resource Recovery



Resources Policy 51 (2017) 100–106



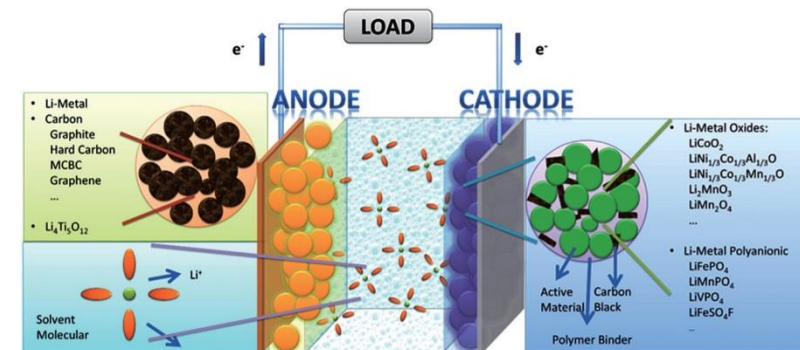
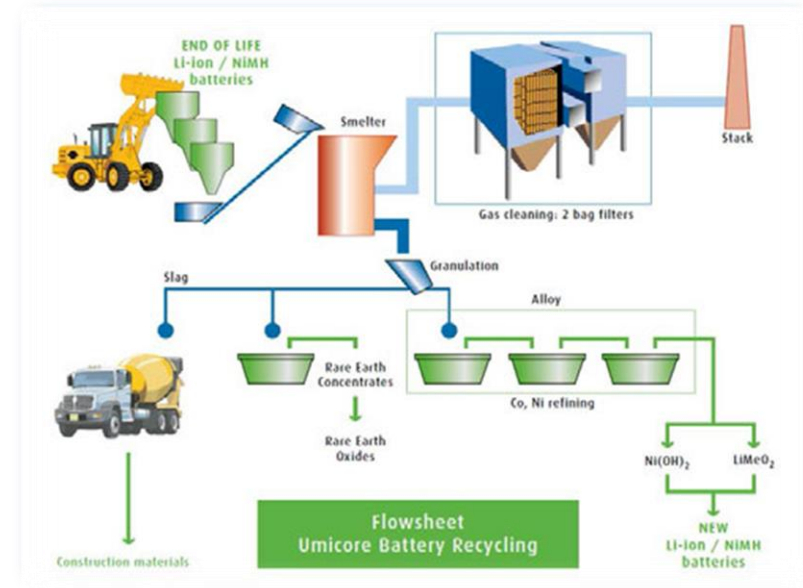
Source: Benchmark Mineral Intelligence



Joule 1, 229–243, October 11, 2017

State of art LIB recycling

- Commercial Smelting: Pyrometallurgy, same as other batteries (**Discharge - Shred – Melt – Recover**)
- High-Temperature required, **Li, Co, Ni, go to slag**, recovered @ **high \$ and energy costs**
- Environmental gas emissions HF, Dioxin etc.

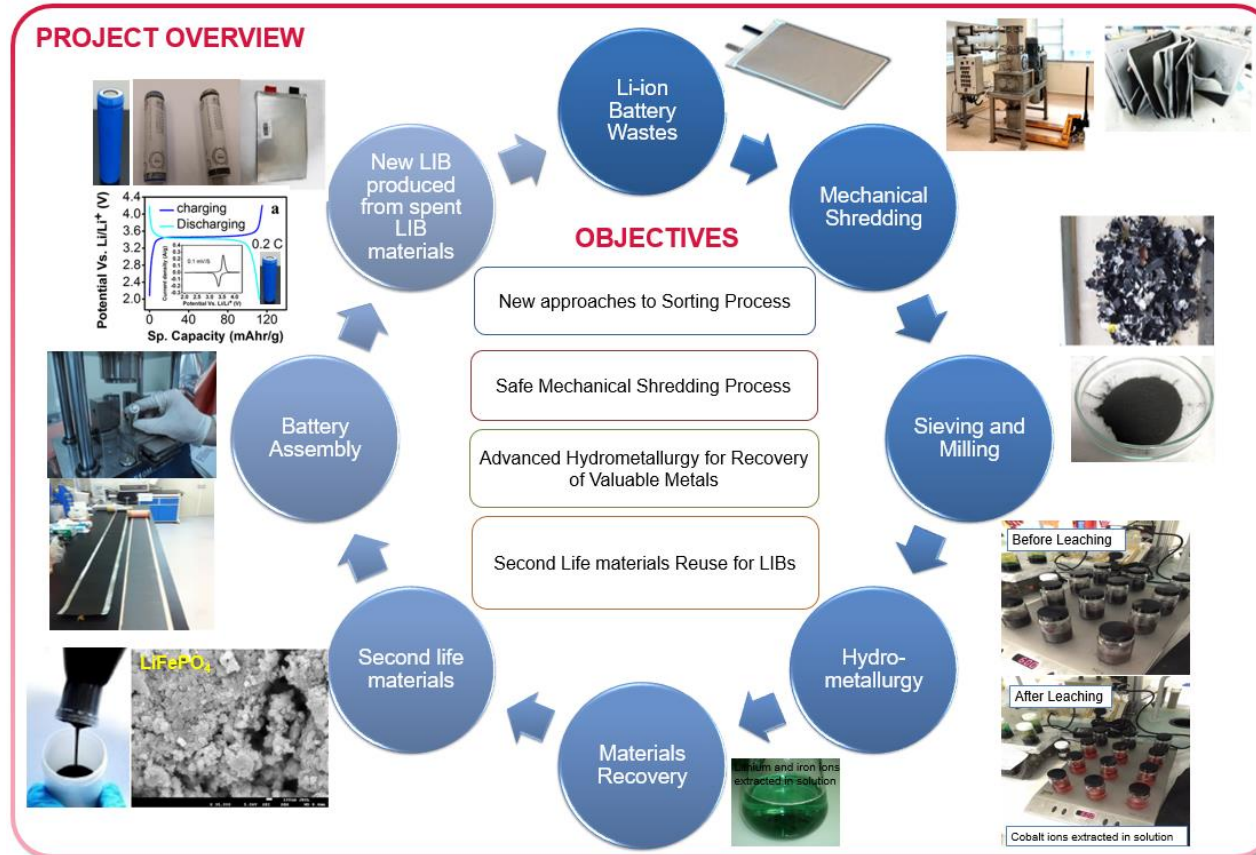


LIB Batteries Recycling Industries



Company	Battery type	Methods
Umicore	Li-, Ni-based	Pyrometallurgy and hydrometallurgy
Retriev	All	Pyrometallurgy (Ni-based) Hydrometallurgy (Li-based) Mechanical process (Pb-acid)
Batrec	Li-, Hg-based	Pyrometallurgy
Accurec	All (except Pb and Hg)	Pyrometallurgy
SNAM	Li-, Ni-based	Pyrometallurgy
Inmetco	Li-, Ni-based	Pyrometallurgy
Recupyl	Li-, Zn-based	Hydrometallurgy
Sony & Sumitomo	All	Pyrometallurgy
Xstrata	Li-, Ni-based	Pyrometallurgy and hydrometallurgy
GEM	Li-, Ni-based	Hydrometallurgy
Brunp	Li-, Ni-based	Hydrometallurgy

Lithium ion batteries (LIB) Recycling process at SCARCE



Circular economy process for lithium ion batteries established at NTU

- New (LIB) from waste used LIB
- Overall high recycling rate (>90%)
- >80% extraction of constituent elements in LIB demonstrated
- Second life reuse of materials demonstrated

Lithium ion batteries shredding

- ✓ Set up a mechanical battery shredder in the SCARCE lab which can shred 10kg/h of various form factor of lithium ion batteries.
- ✓ We have collected over 1000 batteries packs/cells in NTU. Ongoing demonstration of using NTU as test bed for battery recycling.



Used
batteries
collected at
NTU

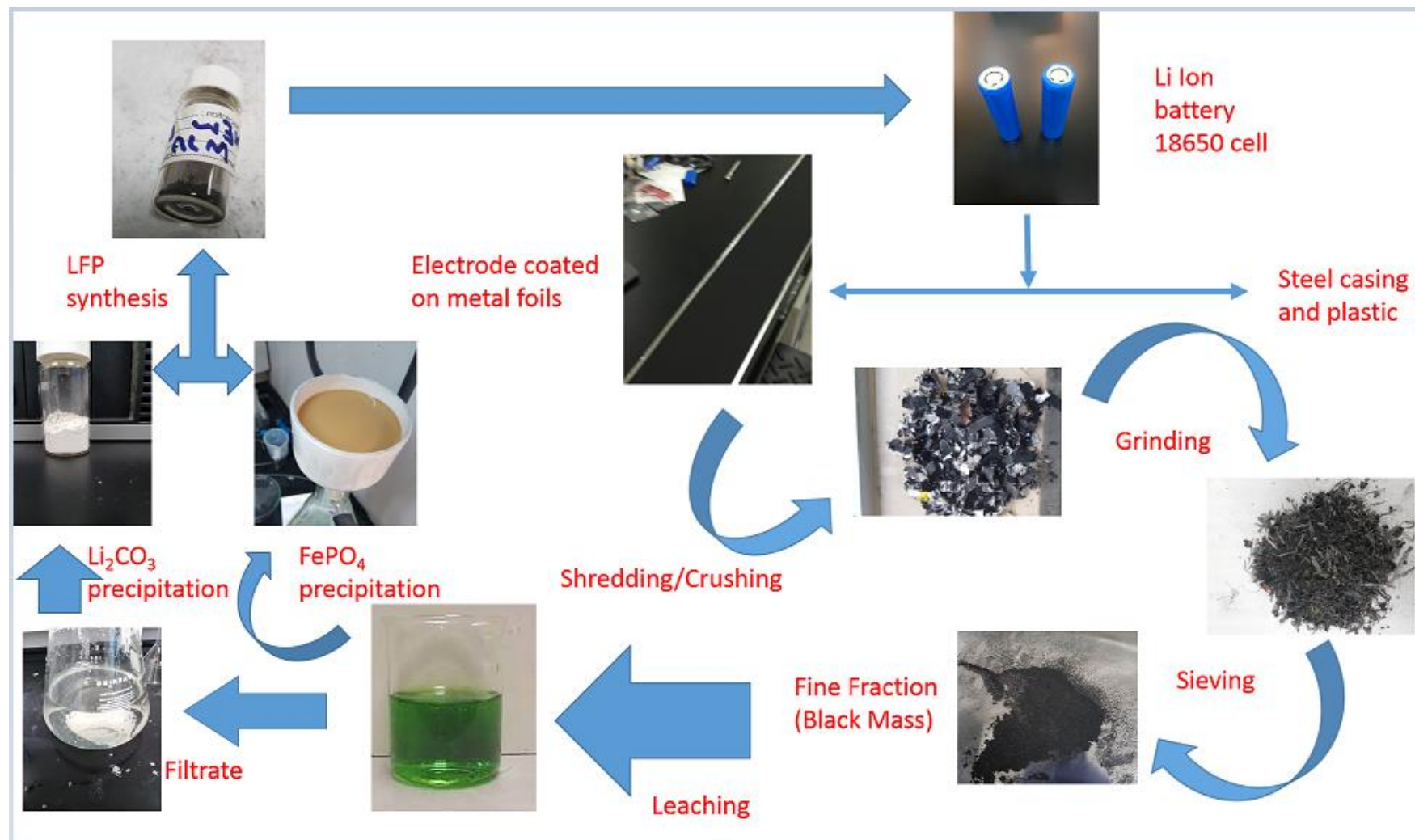


Mechanical Shredder for
batteries (10kg/h)

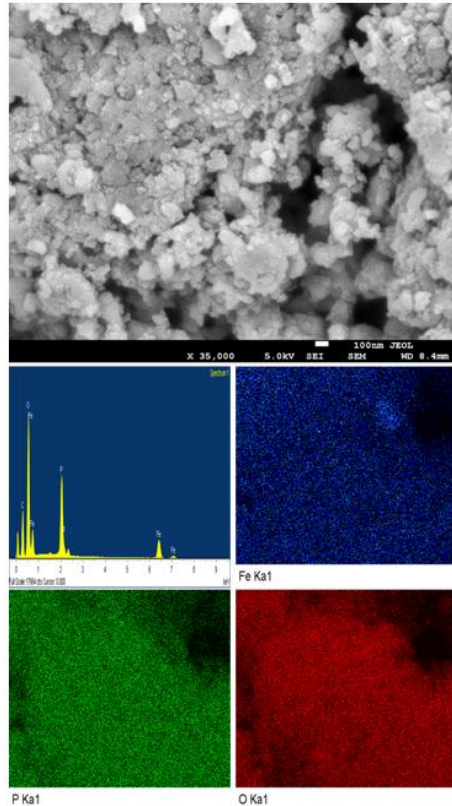


Shredded
batteries

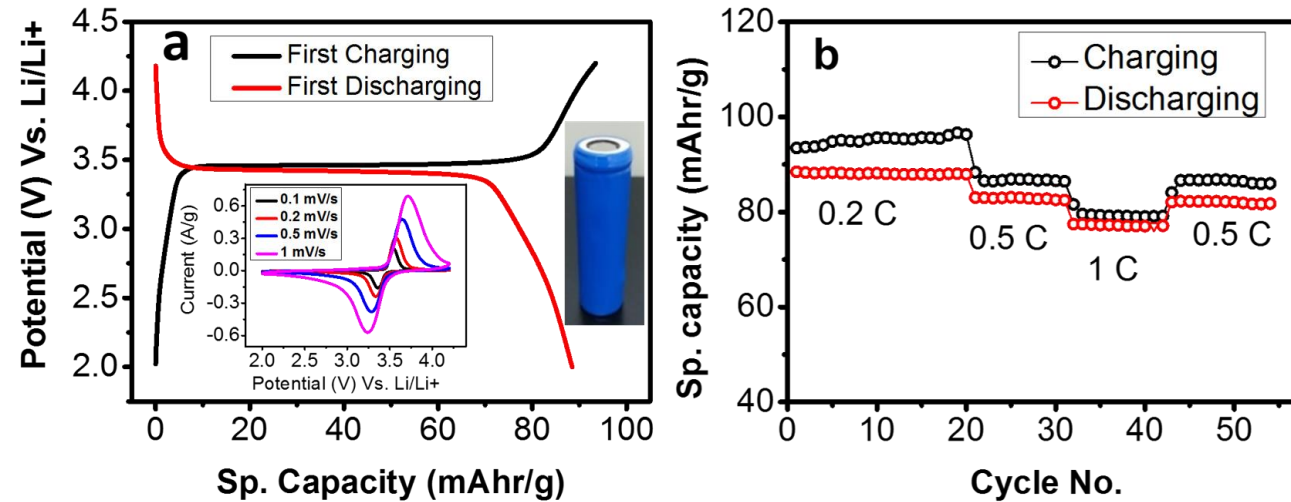
Re-use of materials from old spent lithium ion batteries



New batteries made from elements extracted from old batteries



SEM, EDS and elemental mapping of as synthesized LFP



Electrochemical properties of as synthesized LFP, a) Charge discharge curve at 0.2 C current, (inset CV curve) b) cycling at different C.

Journal of Hazardous Materials 399 (2020) 123068

Fruit Waste to treat battery Waste (WTW) approach

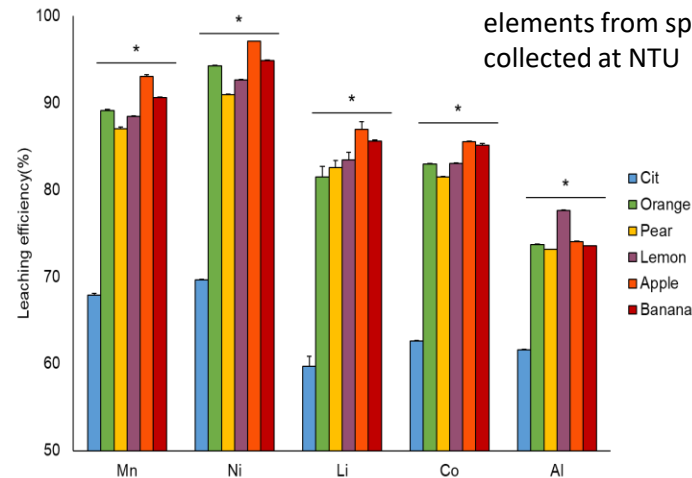


Orange Peel waste



Food waste

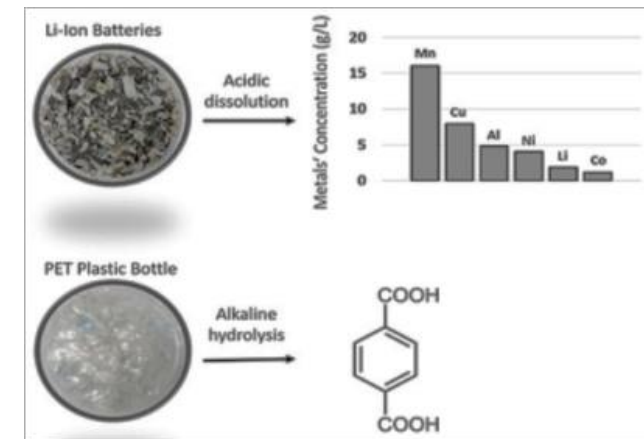
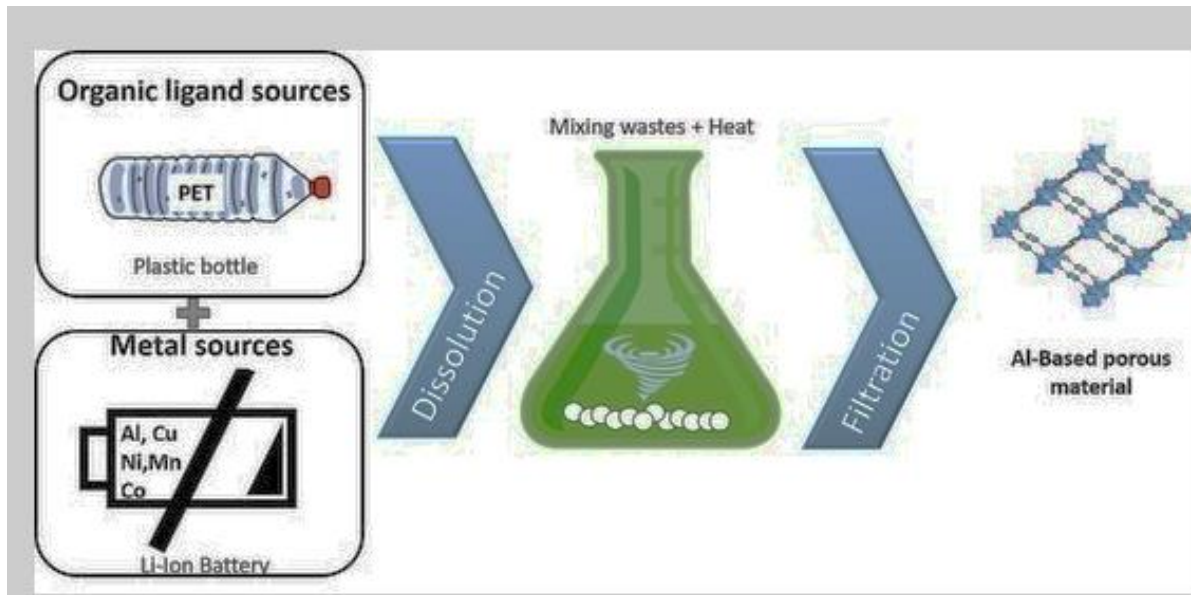
Fruit waste from NTU canteen used to leach out elements from spent LIB collected at NTU



[‘Repurposing of Fruit Peel Waste as a Green Reductant for Recycling of Spent Lithium-Ion Batteries’](#) published in *Environmental Science & Technology* 2020 54 (15), 9681-9692, Madhavi, Dalton et al, DOI: 10.1021/acs.est.0c02873

Recycle plastic bottles and Li-ion battery waste in one process

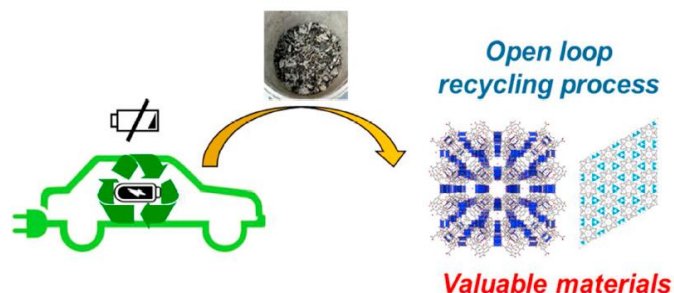
Simple method to recycle plastic-bottle and Li-ion-battery waste in one process by forming valuable coordination polymers (metal–organic frameworks, MOFs).



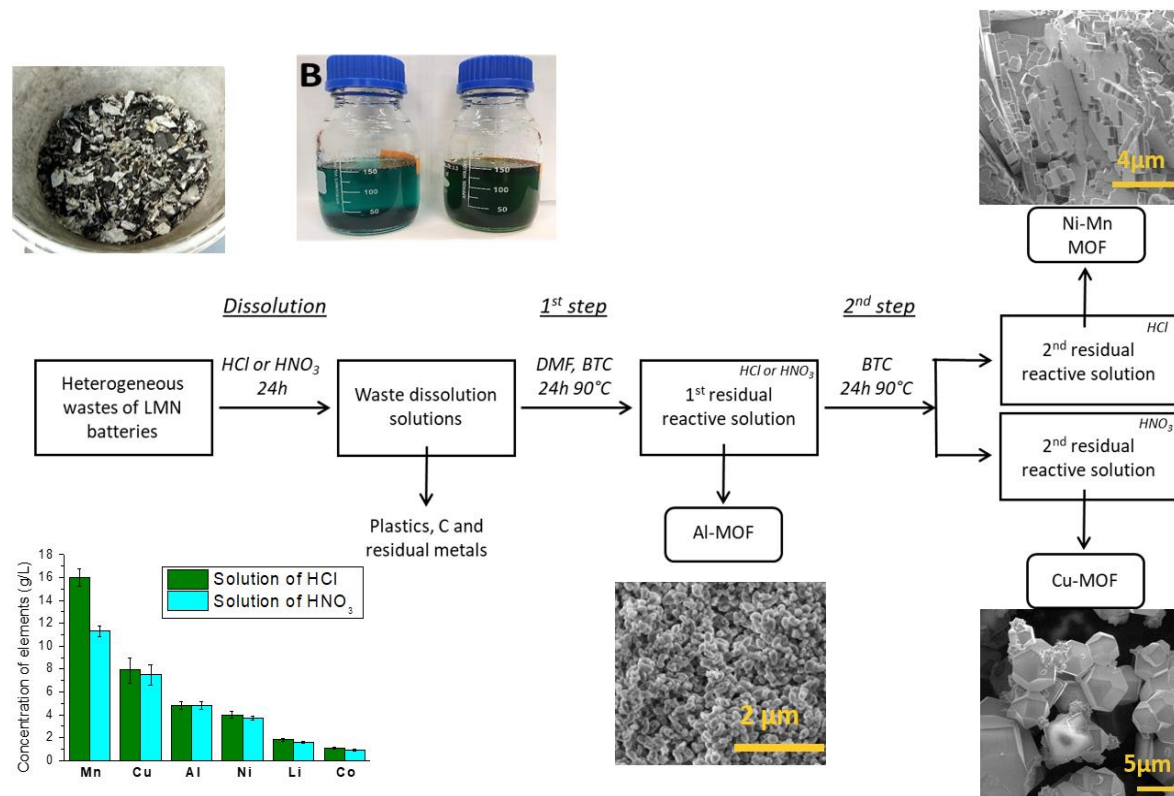
Poly(ethylene terephthalate) from plastic bottles was depolymerized to produce an organic ligand source (terephthalate), and Li-ion batteries were dissolved as a source of metals. By mixing both dissolution solutions together, selective precipitation of an Al-based MOF, known as MIL-53 in the literature, was observed

Materials 2020, 13, 441; doi:10.3390/ma13020441

LIB Waste to high value metal organic frameworks



This method shows promising results at the lab scale (15 g of wastes can be converted in 10 g of MOFs) and opens interesting perspectives for the scaled-up production of MOFs.

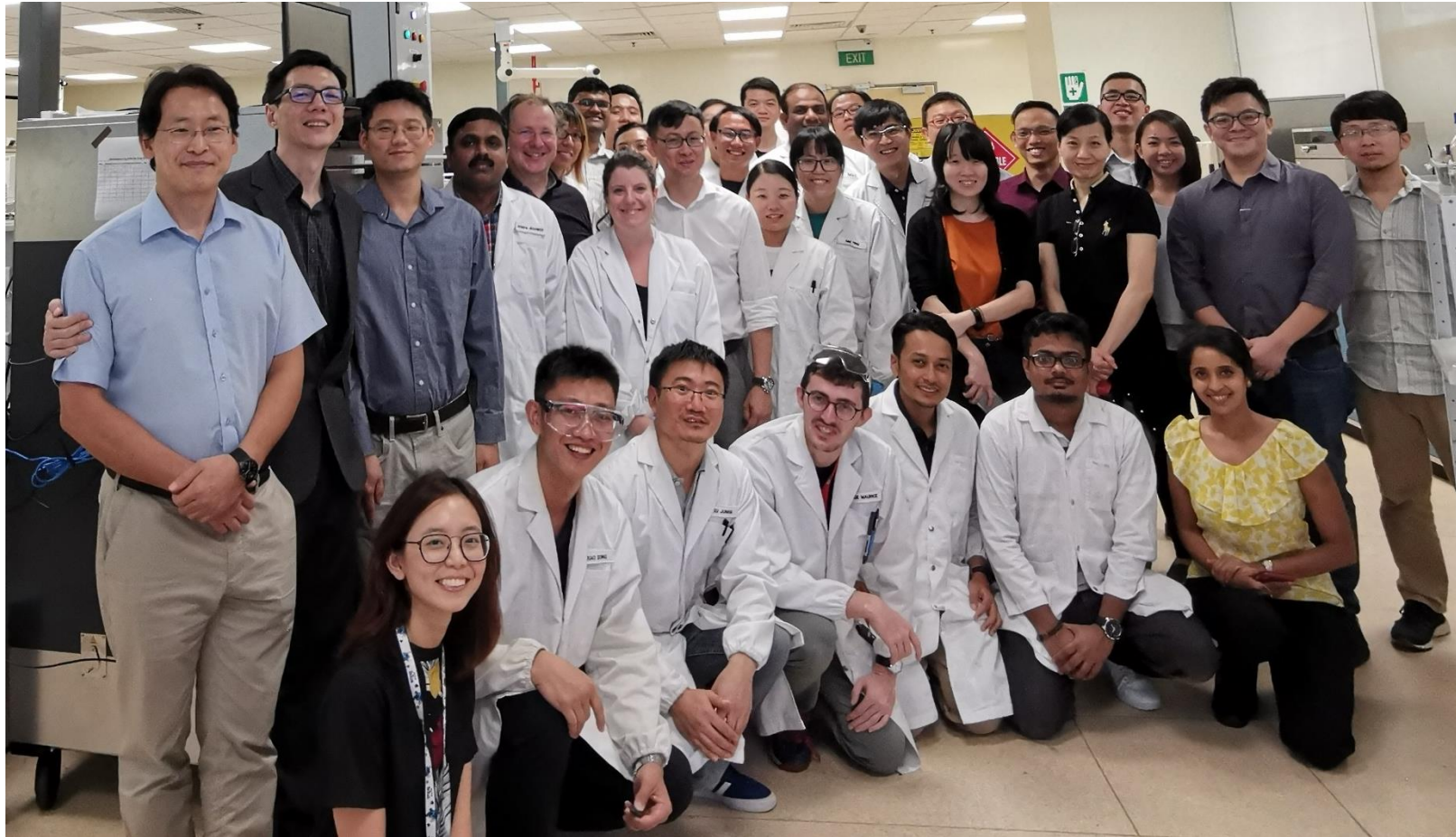




Thank You

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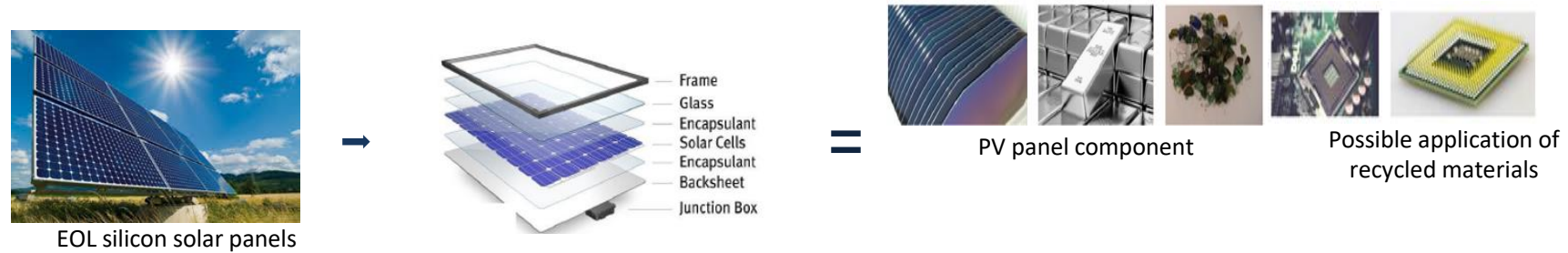
🔗 www.eria.ntu.edu.sg



Thank You



RT2: Recycling of silicon solar panels



- Present techniques only recycle glass, aluminium, copper and steel fractions of the solar cells
- However this results in low value retrieval, and critical materials, such as silver and antimony, as well as the silicon are typically not valorized. New techniques for value recovery is needed



RT3: Recycling and recovery of valuable metals from printed circuit boards (PCBs)



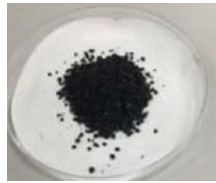
To develop novel recovery processes from PCBs via advanced sorting, mechanical separation and environment-friendly hydrometallurgy techniques.



RT4: Recycling and treatment of plastic parts from e-waste



E-waste plastics



Sorted and grinded component



Possible application of detoxified plastic



Environnement International (2018) 117, P 308-318

To develop novel processes for segregation, detoxification and recycling of plastic parts from e-waste at environment-friendly conditions, and develop possible reuse applications for the recovered materials.

