End-of-Life Challenges of Electric Vehicle Battery

US NSF-CHINA NSF WORKSHOP ON SUSTAINABLE MANUFACTURING

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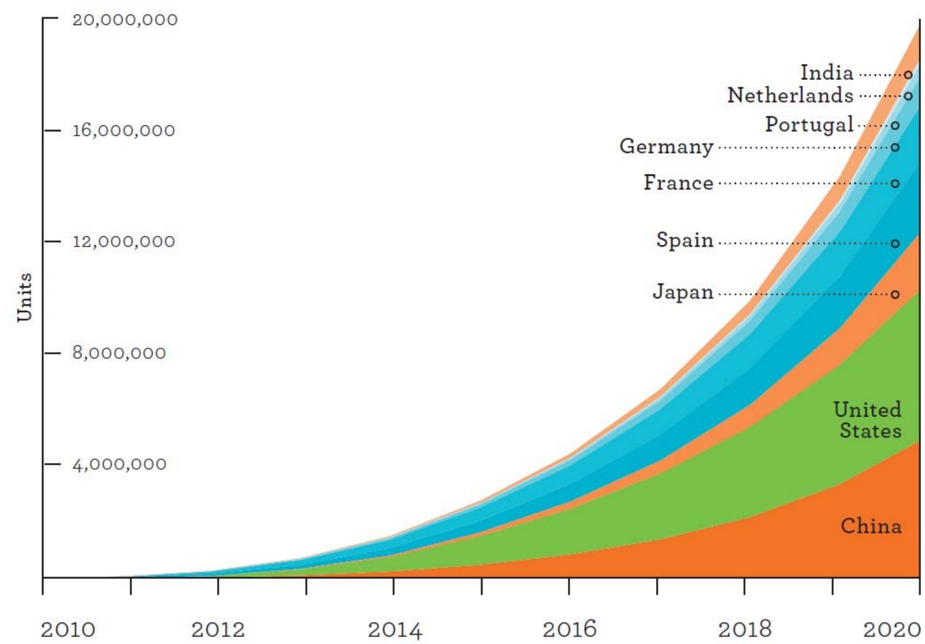
Outline

- Introduction and Problem Statement
- End-of-Life Options
- Laser Cleaning Technology for Remanufacturing
- Conclusions

Introduction and Problem Statement

Electric Vehicle (EV) Market Trend

EV sales have grown and now represent 3.77% of the new car market share in 2013, continuing the steady growth through 2012.



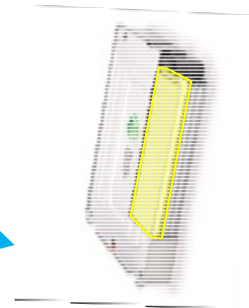
- Tesla's fourth quarter revenue is 20% above previous forecast, with 6,900 Model S sales in fourth quarter

Bloomberg, Jan 15, 2014

Danish Technological Institute case study on electric vehicle (2012)
International Energy Agency, (2013), Bloomberg News

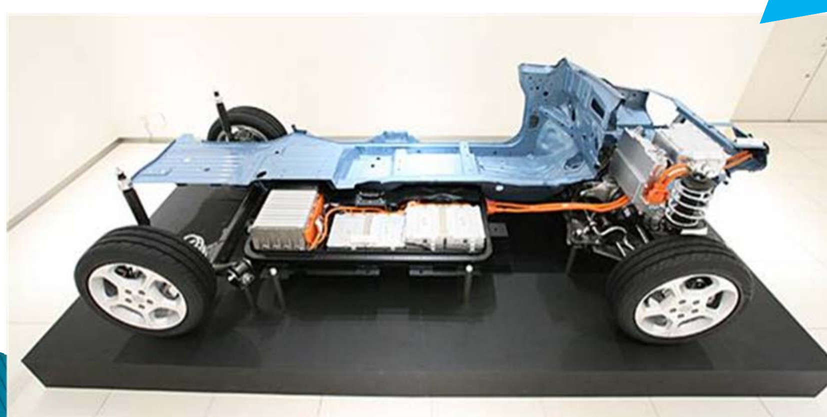
EV Battery Structure

Cell
4 cells/module

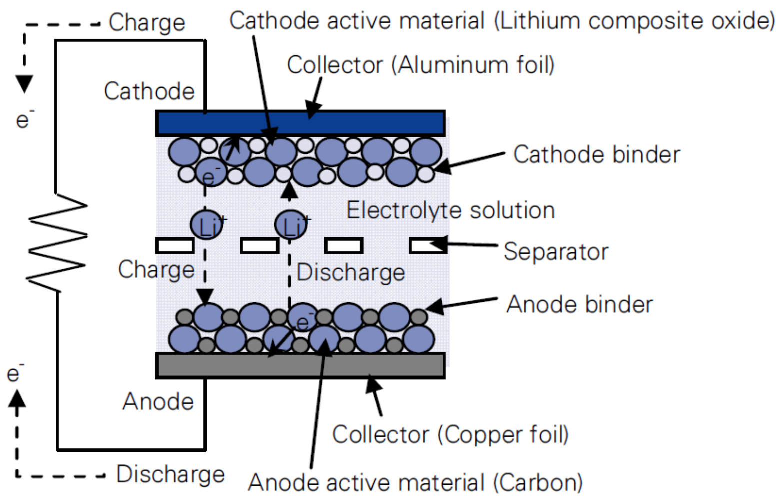


Module
48 modules/vehicle

Battery Pack



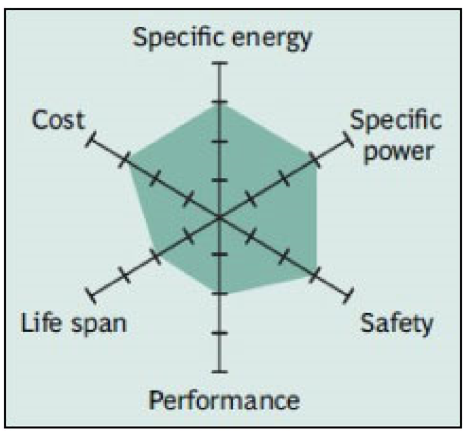
EV Battery Composition



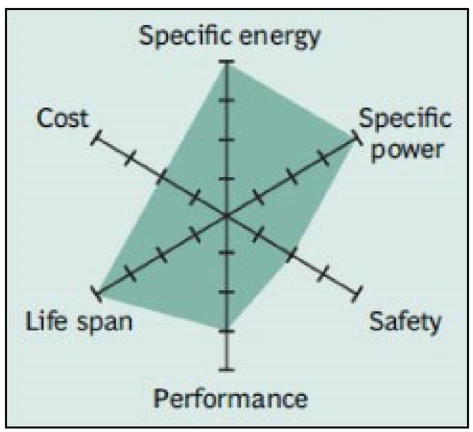
Schematic illustration of inside of LiB

Cathode material for main EV makers:

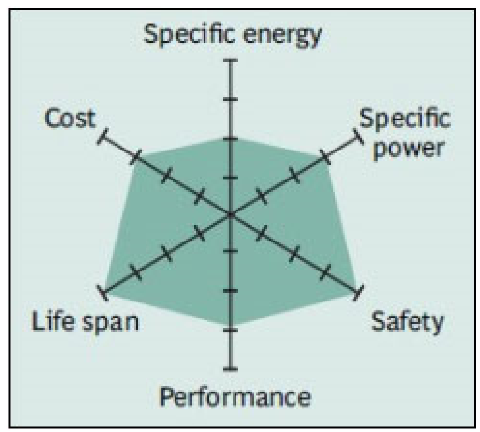
- Nissan Leaf SV: $LiMn_2O_4$, NMC (2015)
- Chevrolet Volt: $LiMn_2O_4$
- Tesla Model S: $LiNiCoAlO_2$
- BYD e6: $LiFePO_4$



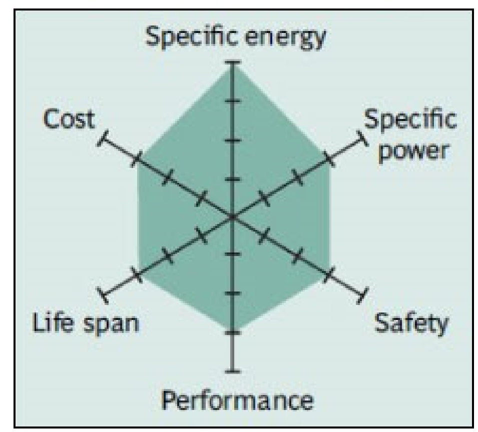
$LiMn_2O_4$



$LiNiCoAlO_2$(NCA)



$LiFePO_4$



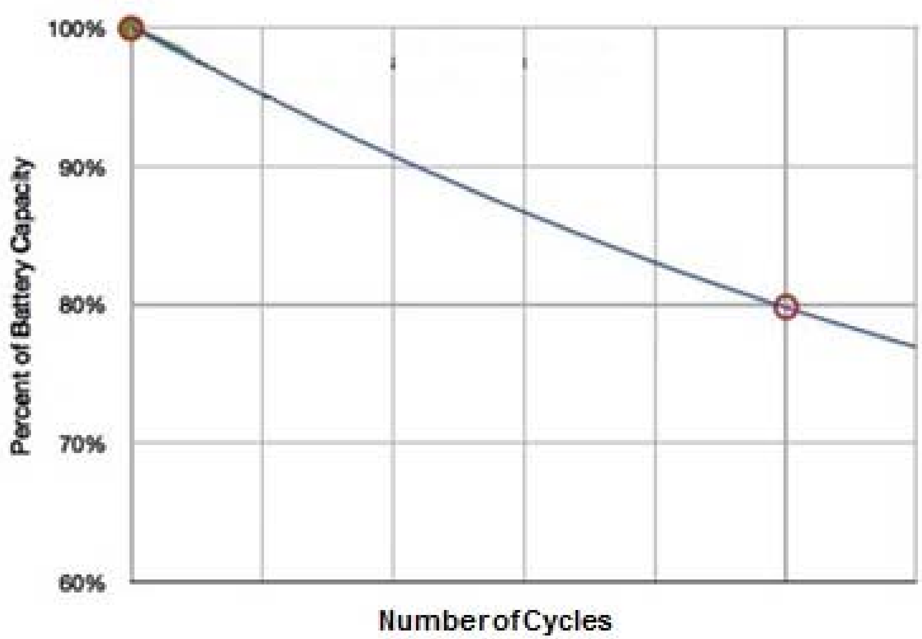
$LiNiMnCoO_2$(NMC)

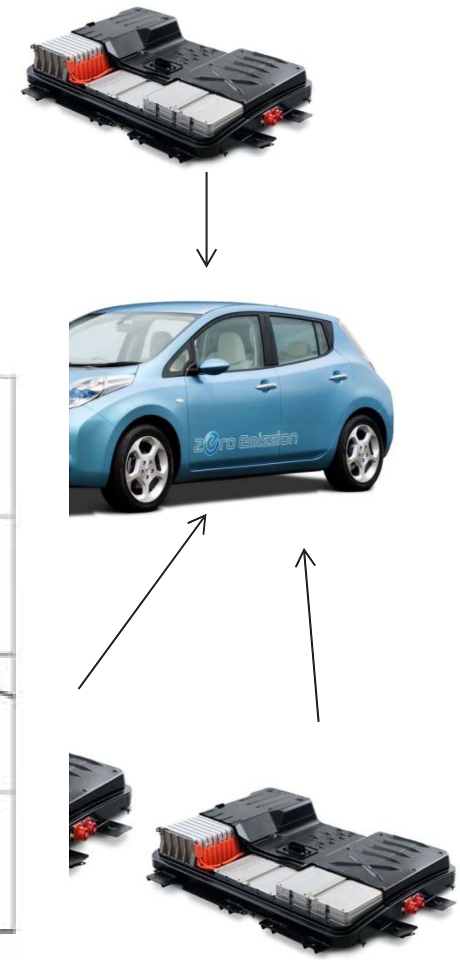
Takato Watabe, Masashi Mori, "LiB materials industry: automotive LiB materials get set for growth phase in 2011", Deutsche Bank Group, January 2011.
The Boston Consulting Group, "Batteris for Electric Cars: Challenges, Opportunities, and the Outlook to 2020", 2010
al. 2011

Problem Statement (1)

- Battery lifespan – usually it is 5-8 years

- High cost of
  - Battery cost ra
    KWh
  - Vehicle life is u
  - 1 or 2 replacer
    required for v



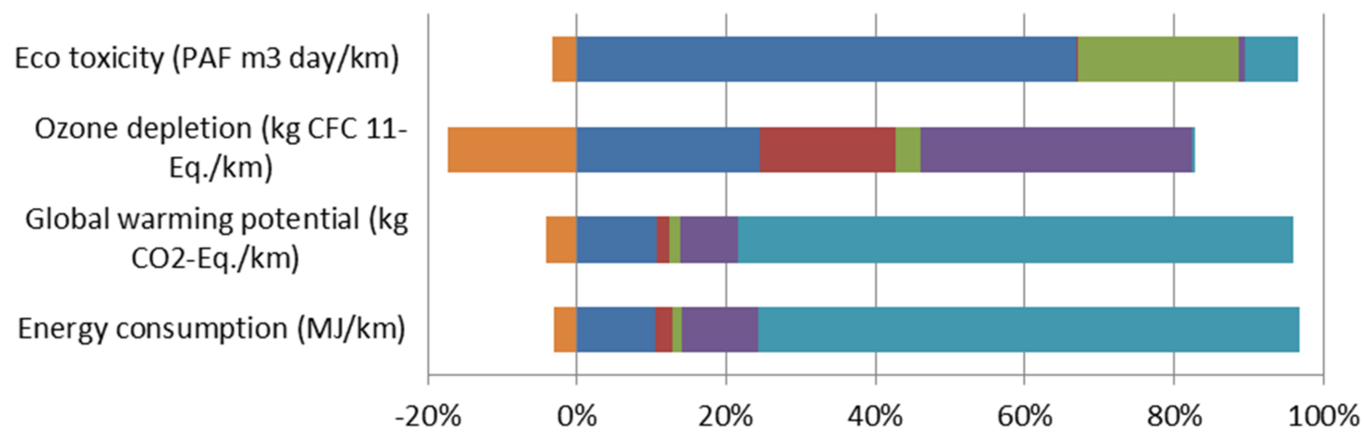


MIT Technology review

Problem Statement (2)

EV battery LCIA results (EPA, 2013),

- Type: $LiFePO_4$
- Lifetime: 10 years
- Capacity: 40 kWh
- Energy usage: 0.1745 kWh/km
- Distance travelled: 19,312 km/year
- Functional unit = 1 km driven

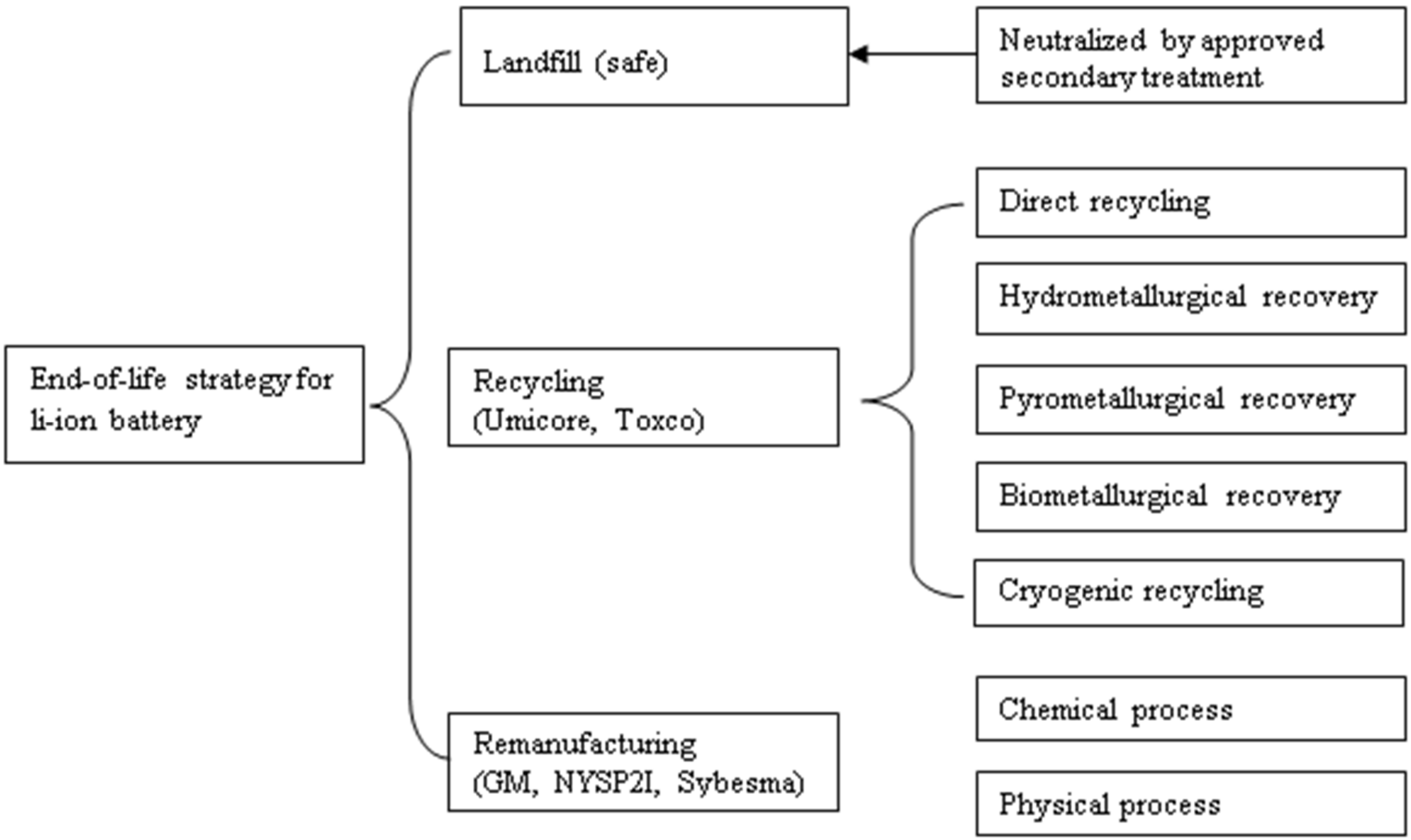


	Energy consumption (MJ/km)	Global warming potential (kg CO2-Eq./km)	Ozone depletion (kg CFC 11-Eq./km)	Eco toxicity (PAF m3 day/km)
Material extraction	2.44E-01	1.73E-02	6.62E-10	4.32E-04
Material processing	5.31E-02	2.85E-03	4.92E-10	1.56E-06
Component manufacturing	2.78E-02	2.23E-03	9.10E-11	1.40E-04
Product manufacturing	2.40E-01	1.26E-02	9.81E-10	4.64E-06
Use	1.68E+00	1.20E-01	9.80E-12	4.66E-05
EOL treatment (recycling)	-7.27E-02	-6.57E-03	-4.66E-10	-2.17E-05

EPA (2013)

End-of-Life Options

End-of-life Options



Landfill

- The U.S. Environmental Protection Agency (EPA) does not regulate the disposal of batteries in small quantities. Large quantities are regulated under the Universal rules of Hazardous Waste regulations (40 CFR PART 273).

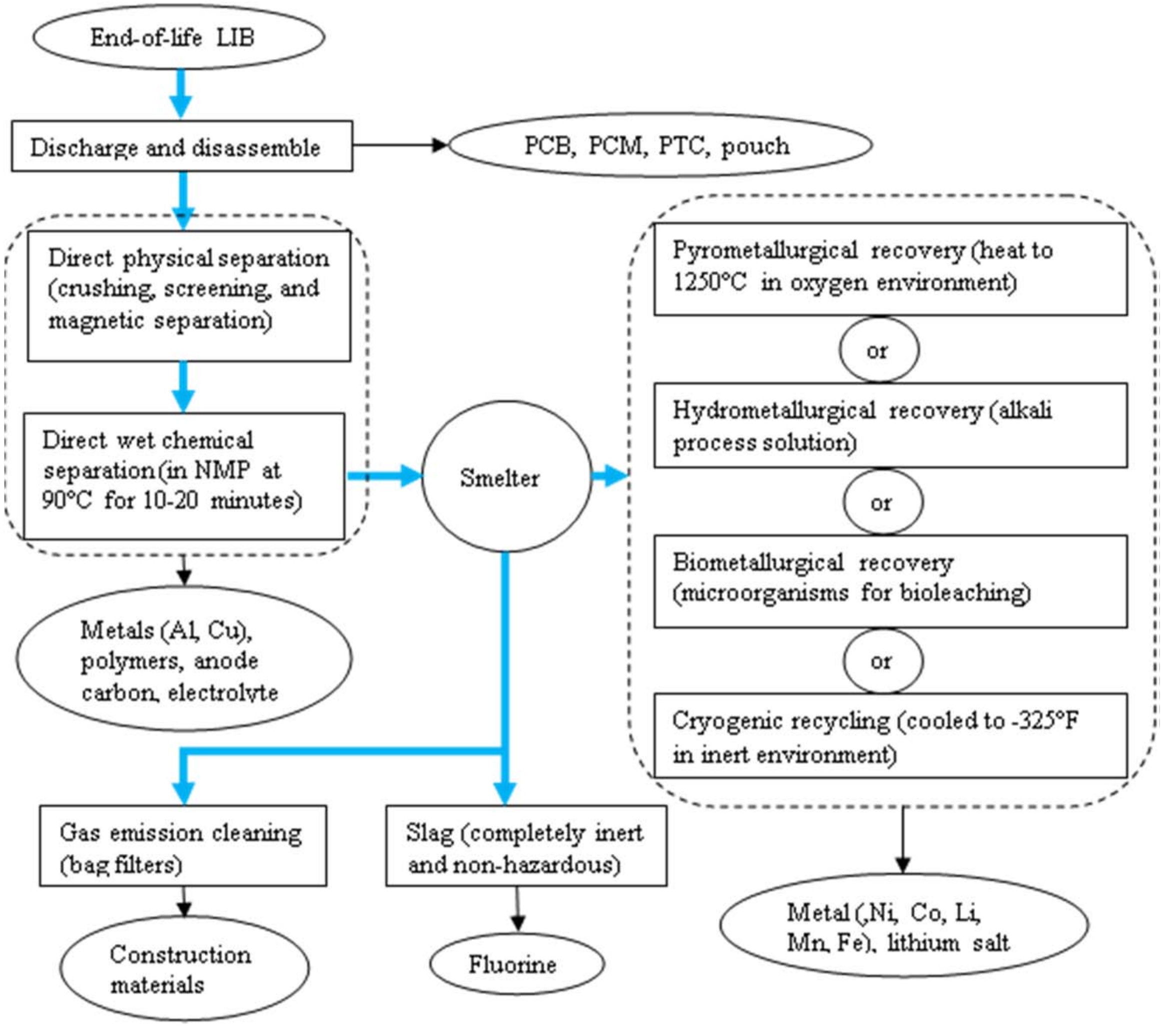
- The shipment of live or discharged lithium batteries is governed by the Department of Transportation (DOT) in their Code of Federal Regulations (49 CFR), paragraph 173.185(j).

- Fire hazard
  (Violent reaction from Lithium with water)

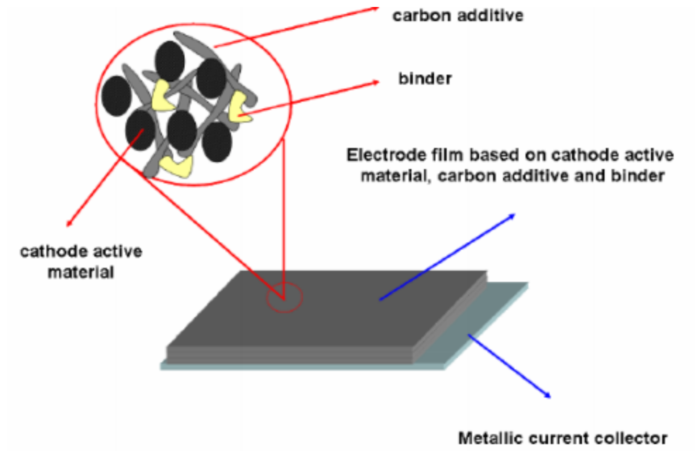
- 80% remaining capacity – Waste of capacity

Recycling Processes

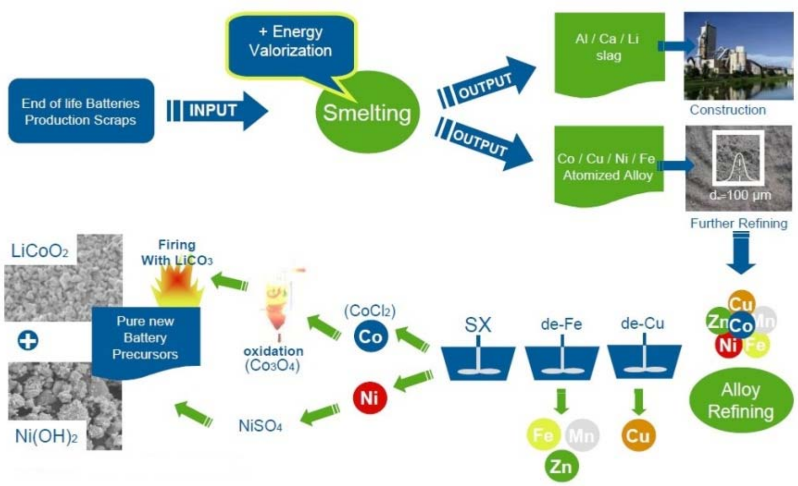
- Various processes combination to recover all relevant materials
- Complex and time-consuming
- Worker health & safety



Challenges for Recycling



Cathode with different materials



Umicore recycling process

- Purity of recovered materials

- High energy use in recycling

  Direct recycling energy use:

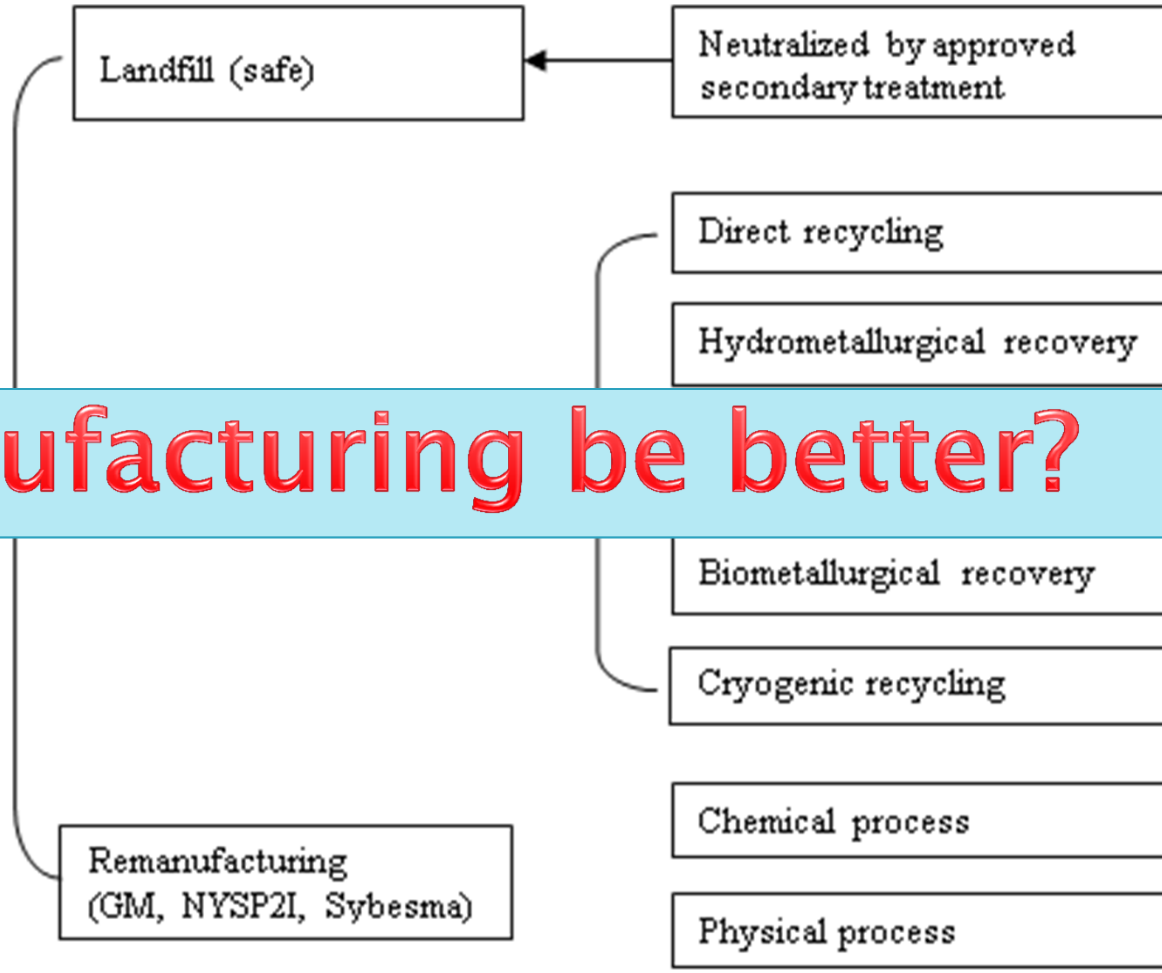
  Separation: 4.4kWh/kg
  Heat treatment: 0.4kwh/kg
  Auxiliaries: 0.1kWh/kg
  Total: 5.0kWh/kg

- Lithium, Aluminum in slag

- 80% remaining capacity – Recycling means waste capacity

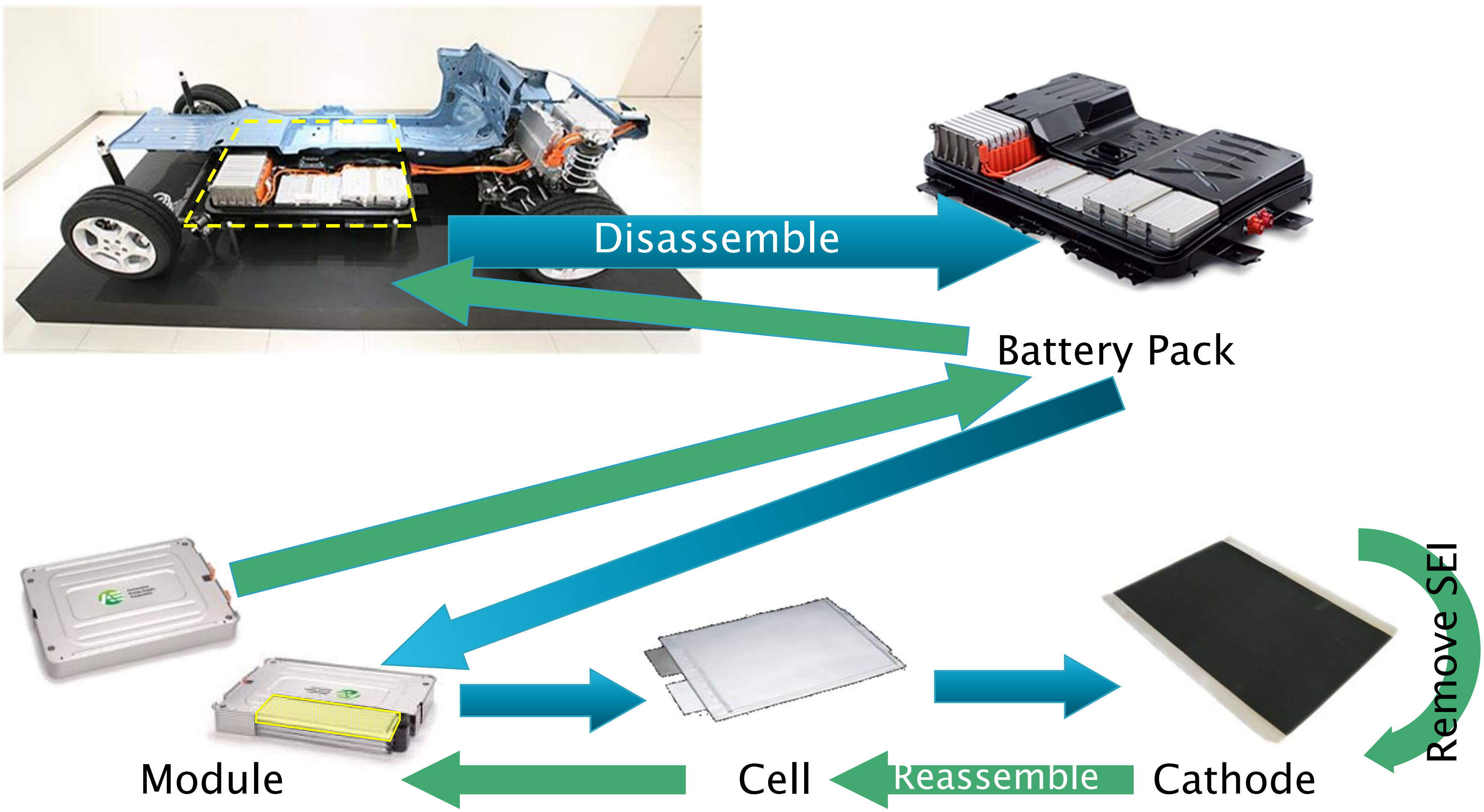
Wang and Zhou(2009) Toxco; Umicore; Gaines, (2011)

End-of-life Options



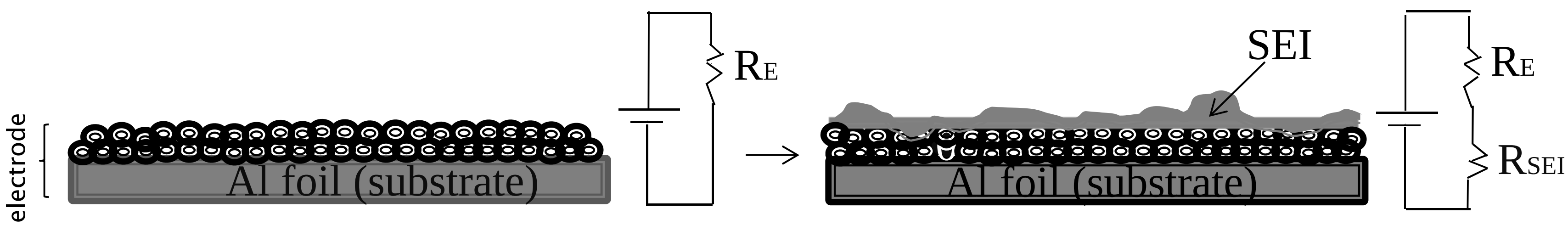
Can remanufacturing be better?

Remanufacturing Process



Remanufacturing: capacity loss analysis

- Electrode at high voltage reacts with the electrolyte forming solid electrolyte interface (SEI) on surface of the electrodes



Schematic diagram of uncycled EV battery

Schematic diagram of cycled EV battery

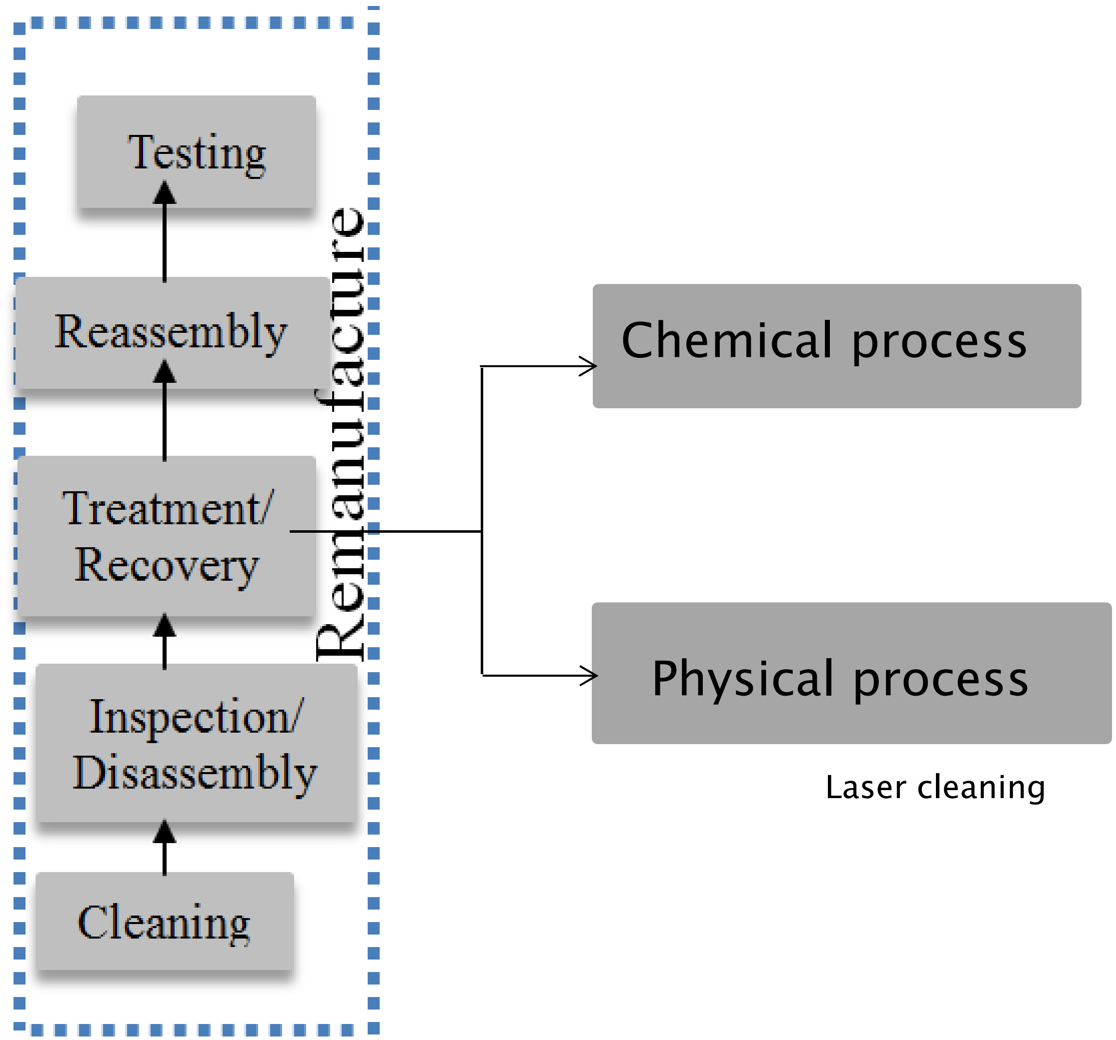
- Surface cleaning of SEI from surface of electrode will enable recovery of electrode.

- Recovery of electrodes leads to the EV battery remanufacture

Abraham et al.(2007), Broussely et al (2011) ,Ramon & Zhang 2013

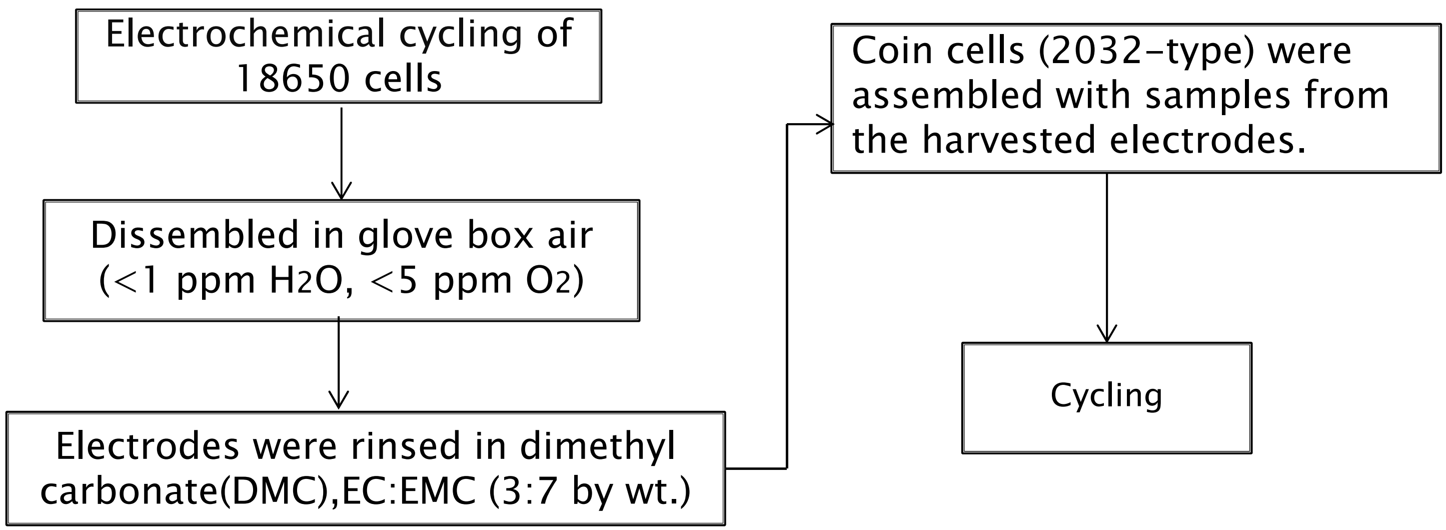
EV Battery remanufacturing

Battery Cell electrode



Chemical Based Process

Abraham et al.(2007):

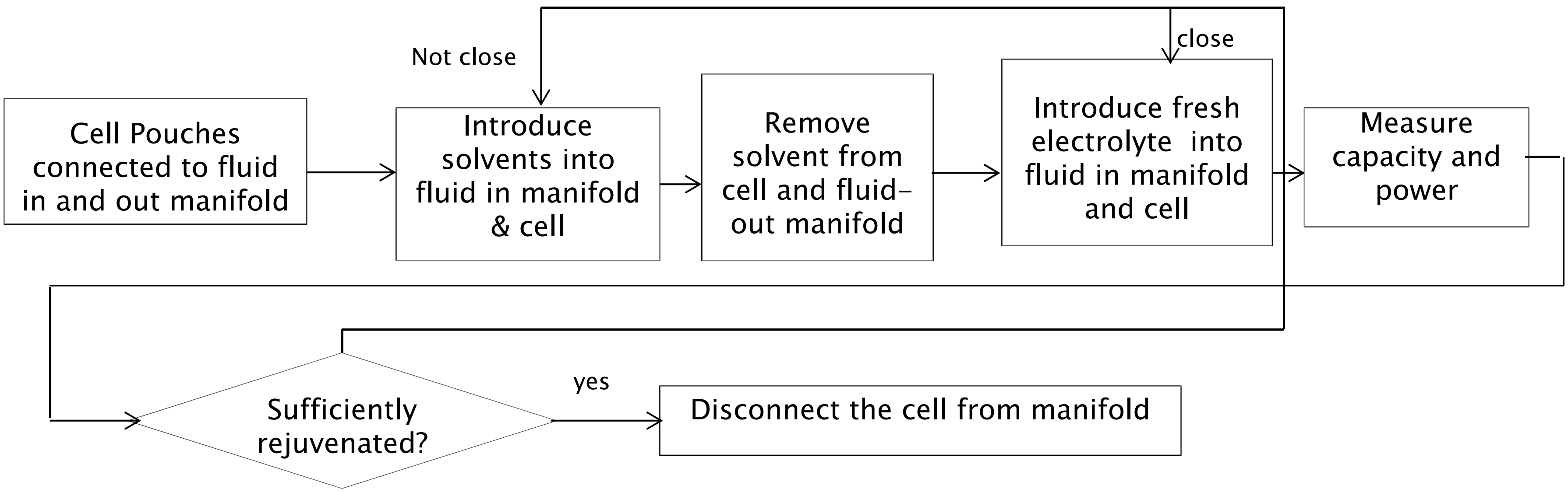


Results: Rinsed electrodes samples showed capacities that were comparable to those of electrodes that were not aged.

D.P. Abrahama,∗, J.L. Knuth a, D.W. Dees a, I. Blooma, J.P. Christophersen/
Journal of Power Sources 170 (2007) 465–475,

Chemical Based Process

GM Applied for Patent for Lithium-ion Battery Cell Refurbishing System using solvents



Process of an exemplary battery rejuvenation method using the pouches and manifolds

Environmental pollutions (Generation of secondary waste)

Impacts measure of using of Ethylene glycol dimethyl	
CO_2 (Global warming potential)	2.1E+0 / kg
NMVOC (human toxicity)	4.2E-3 / kg
Nitrogen oxide (eutrophication)	3.6E-3 /kg
Particulates, < 2.5um (photochemical smog)	3.2E-4/ kg
BOD, (Aquatic eco-toxicity)	1.0E-2/ kg

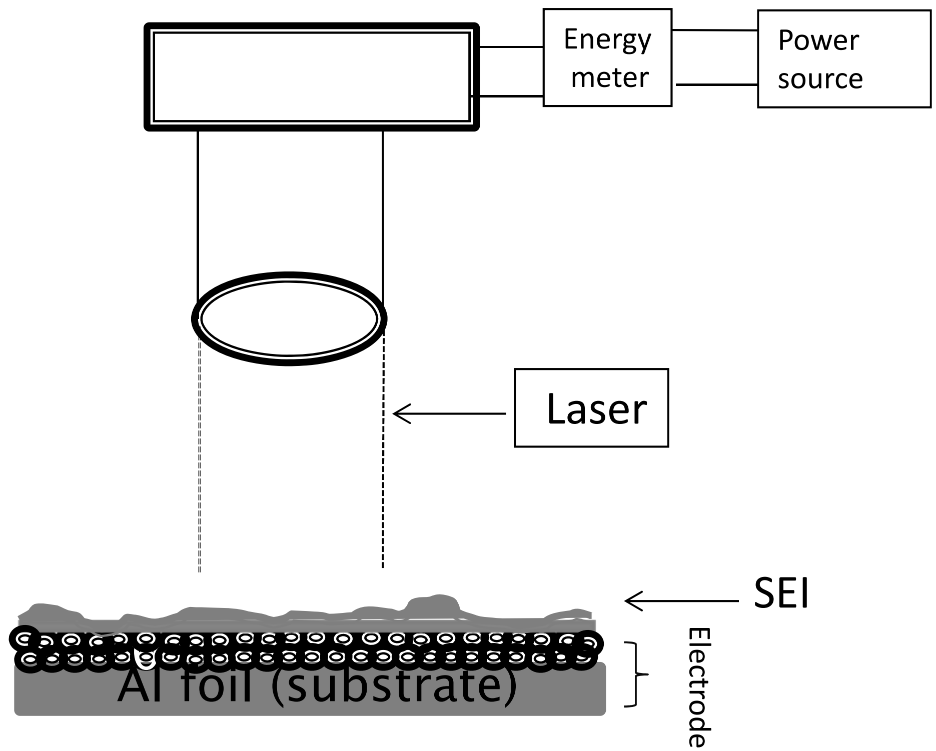
[illegible]www.google.com/patents/US20100124691
http://w[illegible]r/~cardim/PEC/Ecoinvent%20LCA/ecoinventReports/22_PetrochemicalSolvents.pdf

Laser Cleaning Technology for Remanufacturing

Laser based process

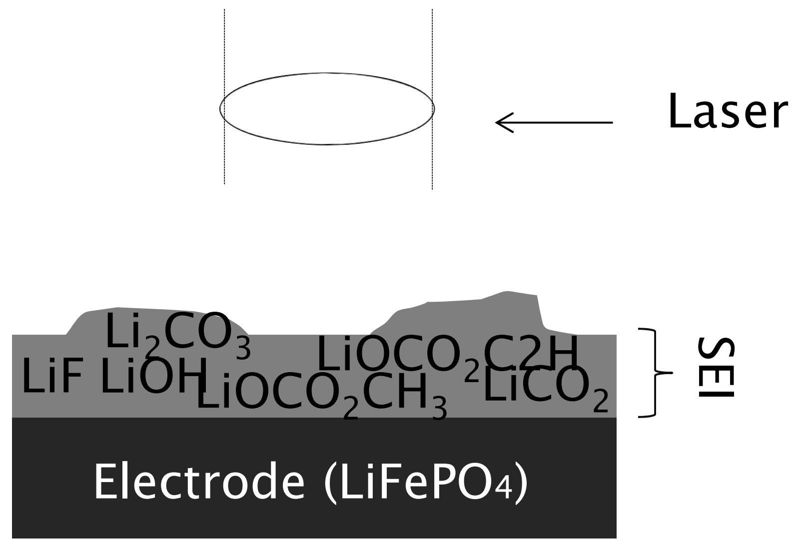
Laser removal of SEI from the surface of the electrode is based on:

- Difference in absorption of laser radiation in SEI and in the electrode.
- SEI absorb laser energy and is ablated with the underlying electrode reflect radiation
- Non-contact self-limiting removal of SEI



Laser removal process

- Molecules of SEI absorb laser radiation via electronic transition into an excited state.
- The excited molecules can reach an unstable state
- when the excitation energy equals the binding energy of the electrons forcing the molecule of the material to fragment.



Bäuerle, D. (2000). *Laser processing and chemistry* (Vol. 3). Berlin: Springer.

Challenges

- SEI is not single compound
- The molecules of some compounds effectively undergo dissociation
- Other compounds might not dissociate readily
- The main challenges:
  - Determination of absorption coefficients of each compound,
  - Aggregation of coefficient for SEI ,
  - Appropriate laser type and its parameters

SEI:

LiF

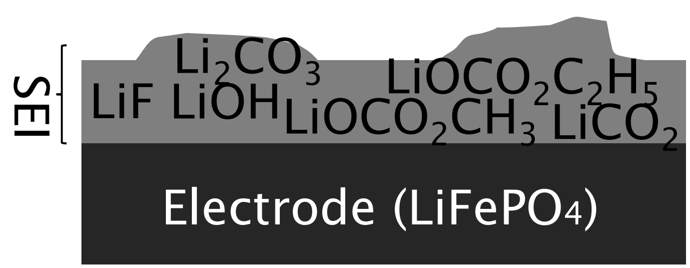
$LiOH$

Li_2CO_3

$LiCO_2$

$LiOCO_2CH_3$

$LiOCO_2C_2H_5$



Conclusions

- EV battery production and end-of-life (EOL) does not positively to pollution reduction
- We suggest remanufacturing has potential to be appropriate EOL option for EV batteries
- Chemical-based remanufacturing will generate secondary waste while we consider laser-based process as a better option
- Significant efforts of research is still required to make laser-based remanufacturing of EV batteries effective

Thank you for attention!