Recent Development of Processes for Recycling Spent Lithium-ion Batteries (LIBs)

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Outline

- Background
- Need for recycling
- Research progress
- Our related work
1. LIBs industry analysis

Asian producers provide most of the LIBs;

In 2020, LG Chem jumps to the largest producer with >100%↑↑
**Electric Mobility: Norway Races Ahead**

Countries with the highest share of plug-in electric vehicles in new passenger car sales in 2019:

- **Norway**: 55.93%
- **Iceland**: 17.79%
- **Netherlands**: 15.01%
- **Sweden**: 11.35%
- **Finland**: 6.89%
- **Portugal**: 5.67%
- **China**: 5.62%
- **Switzerland**: 5.61%
- **Denmark**: 4.17%
- **Ireland**: 4.09%
- **Austria**: 3.47%
- **Belgium**: 3.23%
- **United Kingdom**: 3.15%
- **Germany**: 3.02%
- **France**: 2.77%
- **South Korea**: 2.03%
- **United States**: 1.93%
- **Hungary**: 1.86%

*including plug-in hybrids and light vehicles, excluding commercial vehicles

Sources: ACEA, CAAM, InsideEVs, KAI DA

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**Electric Car Models Set To Triple In Europe By 2021**

Expected number of electric car models available in Europe in late 2019 and in 2021:

- **Volkswagen Group**: 41
- **Daimler**: 23
- **BMW Group**: 21
- **Hyundai-Kia**: 18
- **Peugeot-Citroen-Opel**: 17
- **Renault-Nissan-Mitsubishi**: 17
- **Volvo-Geely**: 16
- **Jaguar-Land Rover**: 16
- **Tesla**: 15
- **Toyota-Lexus**: 13
- **Ford**: 8
- **Others**: 5
- **Fiat Chrysler**: 4

*Includes plug-in hybrid and fully electric models.

Source: Transport & Environment

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**EU buys more EVs; EU market↑↑**

**Future spent batteries in EU**
Types of Commercial LIBs

Cylindrical

Prismatic

Thin and flat

Electrode materials for LIBs

Complexity of electrode materials brings difficulties for recycling

Progress of spent LIBs recycling
2. Need for recycling

Reserves of Some Metal Minerals

- **Ni**: South Africa, 4.94%; Russia, 8.15%; Philippines, 1.47%; New Caledonia, 16.03%; Madagascar, 5.21%; Indonesia, 5.21%; Dominican Republic, 1.30%; Cuba, 7.35%; Colombia, 4.17%; Canada, 4.1%; Brazil, 10.02%; Botswana, 0.65%; Other countries, 6.14%; United States, 0.01%.

- **Co**: Zambia, 3.62%; Russia, 3.35%; New Caledonia, 4.97%; Morocco, 0.27%; Cuba, 6.71%; United States, 0.44%; Canada, 1.88%; China, 1.07%; Other countries, 14.76%; Brazil, 1.19%.

- **Mn**: South Africa, 23.92%; Ukraine, 22.33%; Australia, 15.47%; Brazil, 17.54%; India, 7.81%; Kenya, 0.80%; Kazakhstan, 0.80%; Gabon, 4.31%.

- **Li**: China, 26.99%; Chile, 57.84%; Australia, 7.71%; Brazil, 0.35%; Argentina, 6.56%; United States, 0.29%; Zimbabwe, 0.18%; Portugal, 0.08%; Other countries, 0.29%.
Chile (Li), Turkey (graphite), the Democratic Republic of Congo (Co) and Southeast Asian countries (Ni)
Environmental Hazards of Spent LIBs
Environmental Hazards of Spent LIBs

- **HTP**
  - (10^{-12} cases/km)
  - Graphite
  - SiNW

- **ETP**
  - (10^{-3} PAF m^3 day/km)
  - Graphite
  - SiNW

- **POP**
  - (10^{-3} kg O_3-eq/km)
  - Graphite
  - SiNW

- **ODP**
  - (10^{-10} kg CFC 11-eq/km)
  - Graphite
  - SiNW

- **EP**
  - (10^{-6} kg N-eq/km)
  - Graphite
  - SiNW

- **AP**
  - (10^{-2} kg H^+ Mol-eq/km)
  - Graphite
  - SiNW

- **GWP**
  - (10^{-2} kg CO_2-eq/km)
  - Graphite
  - SiNW

- **ADP**
  - (10^{-4} kg Sb-eq/km)
  - Graphite
  - SiNW
Progress of spent LIBs recycling
Overview on the Recycling Processes

物理法 (Physical treatment)
- 火法 (Thermal treatment)
  - 机械分離 (Mechanical separation process)
  - 研磨过程 (Mechanochemical process)
  - 有机溶剂溶解 (Dissolution process)

化学法 (Chemical treatment)
- 直接合成电极材料 (Direct synthesis of electrode materials)
- 溶胶凝胶法 (Sol-gel method)
- 水热法 (Hydothermal method)
- 共沉淀法 (Co-precipitation method)
- 电化学法 (Electrochemical method)

酸浸过程 (Acid leaching)
生物淋滤 (Bioleaching)
化学沉淀法 (Chemical precipitation)
溶剂萃取法 (Solvent extraction)
电化学法 (Electrochemical process)
Conventional recycling flow

1. Spent LIBs
   - Discharge
   - Pretreatment
   - (Li⁺ containing) Cathode

   - (Li⁺ precipitated as Li₂CO₃)
     - Recovery of Ni, Co, Mn, Li
       - Hydrometallurgy
     - Slags (Li, MnOₓ)
     - Alloy (Co, Ni)

2. Route 1a
   - Hydrometallurgy
     - Recovery of Ni, Co, Mn, Li

3. Route 1b
   - Pyrometallurgy
     - Slags (Li, MnOₓ)
     - Alloy (Co, Ni)

4. Route 2
   - Repair
     - Reusable cathode

5. Route 3
   - Reuse
     - Reusable products

6. Cu/Al foil, Plastic
## Summary of pretreatment method

<table>
<thead>
<tr>
<th>Technology</th>
<th>Detail of methods</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical separation</td>
<td>Separate materials according to different physical properties, like density, conductivity, magnetic behavior, etc.</td>
<td>Simple and convenient operation</td>
<td>Cannot recycle all kinds of components in spent LIBs completely</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>Remove organic additives and binders via thermal treatment</td>
<td>Simple and convenient operation</td>
<td>Require high input of energy, cannot recover organic compounds, and would cause serious exhaust pollution if no exhaust purification device is equipped</td>
</tr>
<tr>
<td>Dissolution process</td>
<td>Dissolve the adhesive substance using special organic reagents</td>
<td>Low energy consumption, and almost no exhaust emission Enhancing the leaching</td>
<td>High cost of organic solvent as well as device investment</td>
</tr>
<tr>
<td>Mechanochemical method</td>
<td>Discording the structure of the materials using grinding techniques</td>
<td>Efficiency of valuable metal and making the reaction condition become mild</td>
<td>High energy consumption and noise problems</td>
</tr>
</tbody>
</table>
Case study: pyrolysis to liberate spent LIBs

Schematic diagram of the combustion/pyrolysis system

Recovery efficiency in each step

Case study: pyrolysis to liberate spent LIBs

99.91% was recycled

99.34% 96.25%

Waste Management (2019).
Case study: pyrolysis to liberate spent LIBs

Ion current intensities of the species within the off-gas during pyrolysis

ACS Sustainable Chemistry & Engineering (2019).
Case study: pyrolysis to liberate spent LIBs

Raw cathode scrap

Pyrolytic cathode scrap
(500°C)
### Summary of leaching efficiency using various liquid medium

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Reagent</th>
<th>Temp. (°C)</th>
<th>Time (min)</th>
<th>Leaching efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inorganic acid leaching</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spent LIBs</td>
<td>1.75 mol/L HCl</td>
<td>50</td>
<td>90</td>
<td>99.0</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>4 mol/L HCl</td>
<td>80</td>
<td>30</td>
<td>90.6</td>
</tr>
<tr>
<td>LiFePO$_4$ and LiMn$_2$O$_4$</td>
<td>6.5 mol/L HCl + 5 vol. % H$_2$O$_2$</td>
<td>30</td>
<td>60</td>
<td>74.1</td>
</tr>
<tr>
<td>LIB industry waste (LiCoO$_2$)</td>
<td>2 mol/L H$_2$SO$_4$ + 5 vol. % H$_2$O$_2$</td>
<td>75</td>
<td>30</td>
<td>94.0</td>
</tr>
<tr>
<td>LiNi$<em>{55}$Mn$</em>{35}$Co$<em>{5}$O$</em>{2}$ compounds</td>
<td>4 mol/L H$_2$SO$_4$ + 5 vol. % H$_2$O$_2$</td>
<td>65-70</td>
<td>120</td>
<td>96.0</td>
</tr>
<tr>
<td>Spent LIBs (mixture)</td>
<td>1 mol/L H$_2$SO$_4$ + 0.075 M NaHSO$_3$</td>
<td>95</td>
<td>240</td>
<td>91.6</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>2 mol/L H$_2$SO$_4$ + 5 vol. % H$_2$O$_2$</td>
<td>75</td>
<td>60</td>
<td>70.0</td>
</tr>
<tr>
<td>(from laptop computers)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>2% H$_3$PO$_4$ + 2 vol. % H$_2$O$_2$</td>
<td>90</td>
<td>60</td>
<td>99.0</td>
</tr>
<tr>
<td>(from mobile phones)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>0.7 mol/L H$_3$PO$_4$ + 4 vol. % H$_2$O$_2$</td>
<td>40</td>
<td>60</td>
<td>99.0</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>1 mol/L HNO$_3$ + 1.7 vol. % H$_2$O$_2$</td>
<td>75</td>
<td>60</td>
<td>95.0</td>
</tr>
<tr>
<td><strong>Alkaline leaching</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spent LIBs (Li(Ni$<em>{1.3}$Co$</em>{1.3}$Mn$_{0.3}$)O$_2$)</td>
<td>4 mol/L NH$_4$·1.5 mol/L (NH$_4$)$_2$SO$_4$ + 0.5 M Na$_2$SO$_4$</td>
<td>80</td>
<td>300</td>
<td>80.7</td>
</tr>
<tr>
<td><strong>Organic acid leaching</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>0.4 mol/L Tartaric acid + 0.02 mol/L Ascorbic acid</td>
<td>80</td>
<td>60</td>
<td>93.0</td>
</tr>
<tr>
<td>Spent LiCoO$_2$ and CoO</td>
<td>1 mol/L Oxalate + 5 vol. % H$_2$O$_2$</td>
<td>80</td>
<td>120</td>
<td>96.7</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>2 mol/L Citric acid + 0.6 g/g H$_2$O$_2$ (H$_2$O$_2$/spent LIBs)</td>
<td>70</td>
<td>80</td>
<td>96.0</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>1 mol/L Oxalic acid</td>
<td>95</td>
<td>150</td>
<td>97.0</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>1 mol/L Iminodiacetic acid + 0.02 M ascorbic acid</td>
<td>80</td>
<td>120</td>
<td>99.0</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>1 mol/L Maleic acid + 0.02 M ascorbic acid</td>
<td>80</td>
<td>120</td>
<td>99.0</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>0.5 mol/L Glycine + 0.02 M ascorbic acid</td>
<td>80</td>
<td>120</td>
<td>91.0</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>1.5 mol/L Succinic acid + 4 vol. % H$_2$O$_2$</td>
<td>70</td>
<td>40</td>
<td>100.0</td>
</tr>
<tr>
<td>Spent LIBs (LiCoO$_2$)</td>
<td>2 mol/L L-tartaric acid + 4 vol. % H$_2$O$_2$</td>
<td>70</td>
<td>30</td>
<td>98.6</td>
</tr>
<tr>
<td><strong>DES leaching</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ChCl and EG (Spent LIBs (LiCoO$_2$))</td>
<td>ChCl:EG=1:2 molar ratio</td>
<td>220</td>
<td>24 h</td>
<td>94.1</td>
</tr>
<tr>
<td>ChCl : urea</td>
<td>ChCl:urea=1:2 molar ratio</td>
<td>180</td>
<td>12 h</td>
<td>97.9</td>
</tr>
</tbody>
</table>
**Typical hydrometallurgical method**

Cathode active materials (Ni, Co, Mn, Li)

Acid/alkaline → Leaching

Leaching solution (Ni, Co, Mn, Li)

Control of pH → Precipitation or extraction

Recovery of Ni, Co, Mn

Solution (Li)

Na₃PO₄ or Na₂CO₃ → Li₃PO₄ or Li₂CO₃

Leaching reactions

\[
3H^+ + \text{LiCoO}_2 = \text{Li}^+ + \text{Co}^{2+} + 1.5\text{H}_2\text{O} + 0.25\text{O}_2
\]

\[
\text{Co}^{2+} + \text{nNH}_3 = \text{Co(NH}_3)_n^{2+}
\]

Extraction reaction

\[
\text{M}_{\text{Aq}}^{2+} + \text{A}^-_{\text{org}} + 2(\text{HA})_{2\text{org}} = \text{MA}_2 \cdot 3\text{HA}_{\text{org}} + \text{H}_{\text{Aq}}^+
\]

Li⁺ precipitation

\[
2\text{Li}^+ + \text{CO}_3^{2-} = \text{Li}_2\text{CO}_3
\]
Leaching and precipitation principles

Removal principle: Fe, Al and Cu ions precipitate at relatively low pH
Deep eutectic solvents (DES) for cathode recycling

EDS to extract valuable metals without using reducing agent

### Summary of industrial recycling method

<table>
<thead>
<tr>
<th>Company/process</th>
<th>Capacity (tonnes/year)</th>
<th>Main products</th>
<th>Technology</th>
<th>Li recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOXCO (Retriv)</td>
<td>4,500</td>
<td>Li$_2$CO$_3$, mixed metal oxides</td>
<td>Hydro-dominant</td>
<td>Yes</td>
</tr>
<tr>
<td>Accurec GmbH</td>
<td>6,000</td>
<td>Co alloy, Li$_2$CO$_3$</td>
<td>Pyro-dominant</td>
<td>Yes</td>
</tr>
<tr>
<td>Inmetco</td>
<td>6,000</td>
<td>Co alloy</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>Green Eco-Manufacture Hi-Tech Co</td>
<td>20,000</td>
<td>NiCo alloy, Ni, Co, Co$_3$O$_4$</td>
<td>Hydro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>Akkuser Ltd</td>
<td>4,000</td>
<td>Metal powder</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>Bangpu Ni/Co High-Tech Co.</td>
<td>3,600</td>
<td>Cathode materials, Co$_3$O$_4$</td>
<td>Hydro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>Sumitomo-Sony</td>
<td>150</td>
<td>Co alloy, Co metal</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>Batrec AG</td>
<td>200</td>
<td>Battery scraps</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>SNAM</td>
<td>300</td>
<td>NR</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>ERAMET (Valdi)</td>
<td>20,000</td>
<td>Raw materials for special steel</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>Nippon Recycle Center Co.</td>
<td>5,000</td>
<td>Raw materials for special steel</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>DK Recycling und Roheisen GmbH</td>
<td>NR</td>
<td>NR</td>
<td>Pyro-dominant</td>
<td>NR</td>
</tr>
<tr>
<td>Umicore</td>
<td>7,000</td>
<td>Ni-Co alloy, NiCO$_3$, NiSO$_4$, CoCO$_3$, CoSO$_4$</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
<tr>
<td>Glencore plc. (Xstrata)</td>
<td>7,000</td>
<td>Co alloy</td>
<td>Pyro-dominant</td>
<td>No</td>
</tr>
</tbody>
</table>
Carbothermic reduction

Recovery rate: Li (93%) and Co (99%)

Waste Management (2019)
Plausible conversion pathways during carbothermic reduction in vacuum

Thermite reduction

Leaching efficiency: Li (99.78%), Ni (98.62%), Co (99.29%), Mn (99.9%)

Journal of Cleaner Production (2020)
Molten salt method

Schematic illustration of molten-salt-electrolysis process

\[ 2\text{LiCoO} + 2e^- = 2\text{CoO} + \text{Li}_2\text{O} + \text{O}^{2-} \]

\[ \text{C} + \text{O}^{2-} - 4e^- = \text{CO}_2 (g) \]

\[ \text{CO}_2 + \text{Li}_2\text{O} = \text{Li}_2\text{CO}_3 \]
Recycling Processes

Umicore Battery Recycling:

✓ Processing 4000 t/a spent Li-ion, Ni-MH batteries and their scraps, higher recovery efficiency, no toxic gases emission;

✓ Pyrometallurgical process, higher energy consumption and cost, Li and Al lost.
Recycling Processes

TOXCO recycling process:

- Recycling more than 35,000 MT spent batteries, and this process gained the Government Services Administration (GSA) granted by US government;
- The only industrial recycling process which can recover Li from spent batteries.
Batrec recycling process:

- Pre-sorting $\rightarrow$ crushing $\rightarrow$ Li Neutralisation $\rightarrow$ multistage separation $\rightarrow$ materials circulation;
- Mechanical processes, lower recovery efficiency, only obtaining coarse products, dust pollution.
Recycling Processes

Demonstration center of recycling process for spent batteries
Recycling Processes

Extraction

Acid leaching

Crystallization

Alkali dissolution

Acid leaching
Recycling Processes

Sorting & crushing → dissolution → separation & purification → aqueous synthesis → high temperature reaction → Resynthesis of cathode materials.
Recycling Processes

- Leaching Line
- Extraction Line
- Synthetic Line
Disadvantages of the existing processes

- Complicated recycling procedures (especially multi-step pretreatment processes)
- High materials and energy consumption
- Low recovery efficiency (mainly due to the incomplete separation of cathode materials and Al foil)
- Secondary pollution to the environment
  - Waste gas: HF, VOCs, et al.
  - Waste water: heavy metals, ammonia, Ros, salts
  - Solid waste: slag, sludge
4. Some examples in ERTE, IPECAS

Pretreatment (physical)

Selective metal recovery

Pollution control

2010
Lab scale

2015
Industrial application

2020
Innovation

Some examples in ERTE, IPECAS

② Inorganic acid leaching process
① Organic acid leaching process
High S/L ratio
High leaching selectivity
High leaching efficiency
pH<1
pKa1<1
pH>1
pKa1>1

Cathode scrap
Leachate
Al foil
+ Leachate
Cathode material

H A
n
H A
n-1

p K a1 = pH - lg (H A)
C
K
C

Sustained released H+
+ Reductant
HCl
Reductant + H+
Ascorbic acid
Pretreatment of spent batteries

Crushing - Electrolyte removal – Mechanical separation – Deep separation

Developed compact set-up (one feed one out)
Selective lithium recovery using formic acid

Selective lithium recovery using formic acid

Comparison of different leaching conditions

Selective metal recovery using ammonical
Selective recovery with advanced oxidation

Green Chem., 2018, 20, 3121-3133
Sulfation roasting method

\[ 2\text{LiNi}_{x}\text{Co}_{y}\text{Mn}_{z}\text{O}_2 + \text{H}_2\text{SO}_4 = \text{Li}_2\text{SO}_4 + 2\text{Ni}_{x}\text{Co}_{y}\text{Mn}_{z}\text{O}_a + \text{H}_2\text{O} + \frac{3-2a}{2}\text{O}_2 \]
Recycling and resynthesizing LiNi$_{1/3}$Co$_{1/3}$Mn$_{1/3}$O$_2$

Distillation

Leachate
35.01% Ni, 35.39% Co, 35.18% Mn, 68.90% Li, 9.31% Al

Separated cathode material
64.98% Ni, 64.60% Co, 64.81% Mn, 31.09% Li, 0.56% Al

Recovered Al foil
0.01% Ni, 0.01% Co, 0.01% Mn, 0.01% Li, 90.13% Al

To be treated

Calcining
700 °C for 5 h

15% NaOH solution
80 °C for 3 h

Washing and drying at 105 °C for 24 h

Removal of conductive agent and organic binder

Removal of impurities (Al)

Composition adjusting

$\frac{n_{\text{Ni}}}{n_{\text{Co}}/n_{\text{Mn}}}=1:1:1$

$\frac{n_{\text{Li}}}{n_{\text{Ni}}+n_{\text{Co}}+n_{\text{Mn}}}=1-1.1$

High temperature solid reaction
450 °C for 5 h, then 900 °C for 20 h, 15 °C min$^{-1}$

LiNi$_{1/3}$Co$_{1/3}$Mn$_{1/3}$O$_2$
Characterization of the LiNi$_{1/3}$Co$_{1/3}$Mn$_{1/3}$O$_2$

- The resynthesized LiNi$_{1/3}$Co$_{1/3}$Mn$_{1/3}$O$_2$: a hexagonal $\alpha$-NaFeO$_2$ structure, highly crystalline and no impurities and secondary phases;
- Ni, Co, Mn and O are distributed uniformly on the surface of the oxide particles.
The impurity Al in the separated cathode material was doped into the matrix of LiNi\(_{1/3}\)Mn\(_{1/3}\)Co\(_{1/3}\)O\(_2\) (NMC). The Al-doped LiNi\(_{1/3}\)Mn\(_{1/3}\)Co\(_{1/3}\)-\(\frac{1}{20}\)Al\(_{1/20}\)O\(_2\) (NMCA) has the same crystal as NMC. However, the electrochemical properties, especially the cycling performance, were enhanced significantly by Al doping.
Pretreatment of spent batteries

- Crushing
- Electrolyte removal
- Mechanical separation
- Deep separation
- Selective lithium recovery
- Ni/Co recovery

New plant is on progress
Estimation of the recycling capacity

Most active areas for battery recycling are still in Asian and European countries

Estimation of spent battery amount

Umicore, Brunp are topping the recycling amount, nearly half (including 3C batteries)
Active worldwide market

Other than Umicore, Brunp, Accurec, Recupyl, HighPower, GEM, Huayou etc.

<table>
<thead>
<tr>
<th>Lead Entity</th>
<th>Location</th>
<th>Year(s)</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Technologies Research Centre Ireland, Ltd.</td>
<td>Paris, France</td>
<td>2017-</td>
<td>88 kWh (Kangoo packs number unspecified)</td>
</tr>
<tr>
<td>Gateshead College, United Technologies Research Centre Ireland, Ltd.</td>
<td>Sunderland, United Kingdom</td>
<td>2017-</td>
<td>48 kWh (3 Leaf packs, 50 kW PV capacity)</td>
</tr>
<tr>
<td>Nissan</td>
<td>Paris, France</td>
<td>2017-</td>
<td>192 kWh (12 Leaf packs)</td>
</tr>
<tr>
<td>RWTH Aachen University</td>
<td>Aachen, Germany</td>
<td>2017-</td>
<td>96 kWh (6 Kangoo packs)</td>
</tr>
<tr>
<td>City of Kempten, the Allgäuer Überlandwerk GmbH</td>
<td>Kempten, Germany</td>
<td>2017-</td>
<td>95 kWh (6 Kangoo packs, 37.1 kW PV capacity)</td>
</tr>
<tr>
<td>City of Terni, ASM Terni</td>
<td>Terni, Italy</td>
<td>2017-</td>
<td>66 kWh (Kangoo packs number unspecified, 200 kW PV capacity)</td>
</tr>
<tr>
<td>Daimler, Getec Energie, The Mobility House, Remondis</td>
<td>Lunen, Germany</td>
<td>2016-</td>
<td>12 MW, 13 MWh (1000 i3 packs, 90% 2nd life)</td>
</tr>
<tr>
<td>Nissan, Eaton, BAM, The Mobility House</td>
<td>Amsterdam, Netherlands</td>
<td>2019-</td>
<td>3 MW, 2.8 MWh (148 Leaf packs, 42% 2nd life)</td>
</tr>
<tr>
<td>Daimler, The Mobility House, GETEC ENERGIE, Mercedes-Benz Energy</td>
<td>Elverlingsen, Germany</td>
<td>by 2020</td>
<td>20 MW, 21 MWh (1878 packs, 40% 2nd life)</td>
</tr>
<tr>
<td>Mobility House, Audi</td>
<td>Berlin, Germany</td>
<td>2019-</td>
<td>1.25 MW, 1.9 MWh (20 e-tron packs, 100% 2nd life)</td>
</tr>
<tr>
<td>UPC SEAT, Endesa</td>
<td>Malaga, Spain</td>
<td>2016-</td>
<td>37.2 kWh (4 PHEV packs, 8 kW PV)</td>
</tr>
<tr>
<td>BMW, Vattenfall, Bosch</td>
<td>Hamburg, Germany</td>
<td>2016-</td>
<td>2 MW, 2.8 MWh (2600 i3 modules)</td>
</tr>
<tr>
<td>Renault, Connected Energy Ltd</td>
<td>Belgium</td>
<td>2020-</td>
<td>720 kWh, 1200 kW (Kangoo packs number unspecified)</td>
</tr>
<tr>
<td>Nissan, WMG: University of Warwick, Ametek, Element Energy</td>
<td>United Kingdom</td>
<td>2020-</td>
<td>1 MWh (50 Leaf packs)</td>
</tr>
<tr>
<td>UC Davis, California Energy Commision, Nissan</td>
<td>Davis, CA, USA</td>
<td>2016-</td>
<td>260 kWh (864 Leaf modules, 100 kW PV)</td>
</tr>
<tr>
<td>BMW, EVgo</td>
<td>Los Angeles, CA, USA</td>
<td>2018-</td>
<td>30 kW, 44 kWh (2 i3 packs)</td>
</tr>
<tr>
<td>UC San Diego, BMW, EVgo</td>
<td>San Diego, CA, USA</td>
<td>2014-2017</td>
<td>108 kW, 180 kWh (unspecified number of mini E packs)</td>
</tr>
<tr>
<td>General Motors, ABB</td>
<td>San Francisco, CA, USA</td>
<td>2012</td>
<td>25 kW, 50 kWh (5 Volt packs, 74 kW PV, 2 kW wind turbines)</td>
</tr>
<tr>
<td>Toyota</td>
<td>Yellowstone National Park, USA</td>
<td>2014-</td>
<td>85 kWh (208 Camry modules)</td>
</tr>
<tr>
<td>Nuvve, University of Delaware, BMW</td>
<td>Newark, USA</td>
<td>2019-</td>
<td>200 kW (unspecified number of mini E packs, integrated with V2G in addition)</td>
</tr>
<tr>
<td>Nissan Sumitoto (4R Energy), Green charge network</td>
<td>Osaka, Japan</td>
<td>2014-</td>
<td>600 kW, 400 kWh (16 Leaf packs)</td>
</tr>
</tbody>
</table>
Summary

- Technology development toward cleaner and smarter
- Short cut process is required including selective recovery and materials regeneration
  
  *(direct regeneration is not possible currently because of severe impurity level control requirements)*
- Whole process shall be considered in order to achieve zero emission
Thank you!

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