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- Producers responsibilities
- Calculation of the Recycling Efficiency
- BD and ELV

Battery recycling technology
- General concepts and challenges
- Umicore Battery Recycling
  - process description
  - RE-calculation applied
(H)EV Battery Recycling: legislative context
Why Battery Recycling?
Part of the clean mobility global picture

<table>
<thead>
<tr>
<th>Choice of transport mode</th>
<th>Clean vehicles</th>
<th>Clean energy</th>
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<tbody>
<tr>
<td>Exhaust control</td>
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<td>Electrification</td>
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<tr>
<td>Vehicle and battery recycling</td>
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Why battery recycling?

- EHS concern: EV-Batteries = a complex mixture of chemical elements and compounds:
  - Li-ion: H, Li, C, O, F, Al, (Si), P, (Ti), Mn, Fe, Co, Ni, Cu, (Sn)
  - NiMH: H, C, O, K, Fe, Co, Ni, La, Ce, Pr, Nd
  - Electrolyte, solvent, plastics…

- Legislative context in EU
  - End of Life of Vehicles Directive (ELV): removal of batteries
  - Batteries Directive: ban on incineration and landfill of industrial batteries
    - To avoid dissemination of hazardous compounds
    - Resource efficiency
    - Quality target: recycling efficiency (RE) ≥ 50 %
      RE = (battery recycled materials)/(battery input materials on dry basis)
BD: Producers obligations regarding recycling

- Basic principle:
  - Extended Producer Responsibility
  - Producer = any person in a Member State that… places batteries or accumulators, including those incorporated into appliances or vehicles, on the market for the first time within the territory of that Member State on a professional basis for same type of EV, sold in different countries, ‘battery Producer’ can be different

- (H)EV batteries are ‘industrial’ batteries, not automotive batteries (= limited to SLI-batteries).
  - no collection target, but take-back obligation (reuse, recycling)

- Recycling Efficiency target (RE)
  - 50% of battery weight has to be transformed into an output fraction that has ceased to be waste or that will be used for their original purpose or for another purpose (without undergoing further treatment).
Calculation of the Recycling Efficiency

- the Battery Directive’s RE is a process efficiency indicator
  - Calculated per calendar year
  - On process/operator level:
    - 2 operators with ‘same’ process = different processes
    - 1 operator with 2 processes = different processes
    - 1 operator processing different battery chemistries together = same process
  - Refers to ‘recycling’ only, not including other recovery (energy).
  - Including all steps until the ‘end of recycling’ (output fractions with a ‘purpose’ without further treatment)

⇒ All batteries processed during the same year in the same process generate 1 RE!

- the Battery Directive’s RE is calculated on ‘battery level’
  - Non-battery materials, e.g. casing of battery packs, are excluded
  - EV-battery assemblies are not considered as ‘packs’ but as ‘batteries’
  - Battery cells are also considered as batteries

- Reporting: responsibility of first recycler (= operator that ‘breaks’ the battery)
  - ⇒ consolidation of all subsequent recycling operations
Calculation of the Recycling Efficiency

Considered as ‘battery’: breakdown of battery = 1st recycling step; agglomerated RE includes partial RE of all subsequent process steps

Non-active battery parts recycled according to existing schemes: partial RE (calculated according to BD) to be reported to ‘1st recycler’

Active battery parts recycled according to dedicated battery recycling schemes: partial RE to be reported to ‘1st recycler’

50 % target applicable, when offered as such to recycling company

50 % target applicable, when offered as such to recycling company
Calculation of the Recycling Efficiency

Impact of material choices of non-active parts

- Based on interviews, Recharge\(^1\) concluded that relative % (w/w) of cells varies between 40-70% of (H)EV battery assembly weight; metals: 15-40%; plastics: 10-15%. Main difference is OEM’s choice for protective casing material (metal or synthetic fibres)
- For same partial RE for each material flow, resulting agglomerated RE can vary significantly

\[\text{Composition} = \begin{array}{ccc} \text{Cells} & \text{Metals} & \text{Plastics} \\ \text{Partial RE} & 50 & 95 & 10 \\ \text{Composition} & 50 & 40 & 10 \\ \text{Partial RE} & 25 & 35 & 1 \\ \text{Composition} & 70 & 15 & 15 \\ \text{Partial RE} & 35 & 14.25 & 0.15 \\ \end{array} \]

\(^1\)Recharge is the European sector association for the advanced rechargeable batteries industry (http://www.rechargebatteries.org/)
Consolidation of batteries RE in ELV reporting

1) Battery to recycling

- Battery to recycling; recycling target = 50%
- Battery recycling to be included in ELV reporting
- Car recycling target = 85%; reuse&recovery target = 95 %

2) Battery to refurbishment for reuse

- Battery considered as 100 % reused for ELV reporting
- Rejected cells/modules subject to recycling target 50%
- Car recycling target = 85%; reuse&recovery target = 95 %
Consolidation of batteries RE in ELV reporting

- BD RE and ELV recycling rates are other concepts

<table>
<thead>
<tr>
<th>BD</th>
<th>ELV</th>
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<tbody>
<tr>
<td>Process focus</td>
<td>Product focus</td>
</tr>
<tr>
<td>including process steps until end of recycling of all fractions</td>
<td>Materials flow reporting (weight fractions to recycling or landfill)</td>
</tr>
<tr>
<td>Possible to treat also non-vehicle batteries in same process</td>
<td>Does not include recycling steps until the ‘end of recycling’ as defined for batteries</td>
</tr>
<tr>
<td>Recycling only</td>
<td>Also reporting reuse and energy recovery</td>
</tr>
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</table>

- Suggestion: to consider batteries as 100% recycled if delivered to compliant battery recycler
Battery recycling technology
Battery recycling concepts

- All recycling concepts are combinations of ‘pre-treatment’ (disassembling, shredding, pyrolysis) and metallurgical processes (pyro or hydro).
- Optimum combination depends on battery chemistry and design, scale leverage effects, processes, ...
Battery recycling concepts: simplified flow sheet

Several EV-battery recycling schemes are under study, only a few are realized in practice. This scheme reflects the major trends.

Several EV-battery recycling schemes are under study, only a few are realized in practice. This scheme reflects the major trends.

- EV battery
  - dismantling
    - cells/modules
    - auxiliary parts
    - Sorting

    - Shredding?
      - N: Pyrometallurgy
        - Metal alloy
          - Transformation
          - Slag
            - Construction
        - Pyrometallurgy
      - Y: Shredding
        - shredding
        - sorting
          - black mass
            - Metal alloy
              - Transformation
              - Slag
                - Construction
                - Hydrometallurgy
                  - salts of Mn Al Li Co Ni Cu
                    - chemical industry

Existing metals recycling
Existing energy recovery
Battery recycling concepts: challenges

- **Dismantling**
  - Labour intensive: Manual ➔ semi-automated ➔ mechanical breaking
  - Safety: State of Charge?

- **Shredding**
  - Charged batteries + inflammable solvents = fire risk; ➔ inert atmosphere or cryogenic shredding
  - Alternatively: pyrolysis before shredding

- **Pyrometallurgy**
  - Optimum conditions for maximum metal yields

- **Hydrometallurgy:**
  - Robustness of the process to cope with variety of input materials

- **General**
  - Quality of the recycled products: should meet industry standards
  - Cost: complex material flow and (still) small quantities
## Battery recycling concepts: process choices

### Shredding

<table>
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<tbody>
<tr>
<td><strong>Cost</strong></td>
<td></td>
</tr>
<tr>
<td>• smaller fraction to metallurgical process: lower investment cost</td>
<td>• several consecutive operations: more labour cost</td>
</tr>
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</table>

### Life Cycle Assessment (LCA)

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<table>
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<tbody>
<tr>
<td>• more LCA credits for recovered Al (as metal)</td>
<td>• safety risk (fire) requires discharging or shredding under inert shield gas or cryogenic shredding → more LCA burden</td>
</tr>
</tbody>
</table>

### Pyro or hydro

#### Pyro

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<table>
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<tbody>
<tr>
<td><strong>Cost</strong></td>
<td></td>
</tr>
<tr>
<td>• low value metals are recycled at low cost</td>
<td>• need to refine also low value metals (mainly labour cost)</td>
</tr>
</tbody>
</table>

#### Hydro

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<table>
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<tr>
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</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td></td>
</tr>
<tr>
<td>• need of chemicals</td>
<td>• waste water treatment</td>
</tr>
<tr>
<td>• higher credits for recovered materials (however, quality not yet proven)</td>
<td></td>
</tr>
</tbody>
</table>

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Pilot test needed to quantify the effects
Scale leverage effects can significantly influence the conclusion
Umicore Process description

Flowsheet
Umicore Battery Recycling

END OF LIFE Li-ion / NiMH batteries

Smelter

Gas cleaning: 2 bag filters

Stack

Slag

Granulation

Alloy

Co, Ni refining

Ni(OH)$_2$

LiMeO$_2$

NEW Li-ion / NiMH batteries

Construction materials

Rare Earth Concentrate

Rare Earth Oxides

END OF LIFE Li-ion / NiMH batteries

Umicore Process description

Winner of the 2012 European Business Awards for the Environment
RE calculation applied to the Umicore process

- Table 1:
  - Possible example of elemental composition of EV-battery modules *(not an industrial average, not representing a ‘real’ battery)*
  - Calculation of theoretical RE on module level:
    - Metals and P are supposed to end up in the right fraction
    - O is partially recovered in metal oxides (slag) and partially emitted as CO₂ and H₂O
    - C and H are emitted as CO₂ and H₂O
    - F is collected in a waste fraction

### Table 1: calculation of RE on module level

<table>
<thead>
<tr>
<th>modules</th>
<th>Al</th>
<th>Li</th>
<th>Ni</th>
<th>Mn</th>
<th>Co</th>
<th>O</th>
<th>Cu</th>
<th>C</th>
<th>F</th>
<th>P</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>element composition input fraction (%)</td>
<td>12</td>
<td>3</td>
<td>5</td>
<td>12</td>
<td>5</td>
<td>17</td>
<td>10</td>
<td>30</td>
<td>1</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>recycling efficiency per element (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>recycled in output fraction (%)</td>
<td>12</td>
<td>3</td>
<td>5</td>
<td>12</td>
<td>5</td>
<td>8,5</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

RE (rounded) = 57%
RE calculation applied to the Umicore process

- Table 2:
  - Calculation of consolidated RE on battery assembly level for:
    - Typical battery assembly with steel casing
    - Typical battery assembly with synthetic fibre casing

<table>
<thead>
<tr>
<th>RE estimation</th>
<th>steel casing</th>
<th>synthetic fibre casing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>input fraction (kg)</td>
<td>partial RE</td>
</tr>
<tr>
<td>modules</td>
<td>60</td>
<td>57%</td>
</tr>
<tr>
<td>metals</td>
<td>25</td>
<td>98%</td>
</tr>
<tr>
<td>plastics</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>mixed</td>
<td>5</td>
<td>30%</td>
</tr>
<tr>
<td>RE (rounded)</td>
<td>60 %</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

- EV recycling is subject to ELV and BD; BD recycling efficiency is distinguished from ELV recycling rate
- EV battery recycling is a combination of pre-treatment and metallurgical and chemical processes; the optimum combination depends on many variables (volume, battery chemistry and assembly design, investment and labour cost, …)
- Low volume of EV batteries today and the uncertainty of the ultimate cell chemistry, make it difficult to fully assess the cost / benefit ratio of EV battery recycling.
- There is a broad range of battery chemistries and the diversification is still going on. Therefore, an EV-battery recycling process has to be robust, in order to cope with this variety.
- The RE is highly influenced by the composition of non-active parts (mainly the protective casing)
- The Umicore process is compliant with the BD RE targets

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Thanks!