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## REVERSE LOGISTICS OF LITHIUM-BASED DEVICE BATTERIES

**Summary.** In Germany roughly 15.000 tonnes of batteries are recycled every year. New challenges arose as more and more lithium-based batteries entered the market. This article deals with the reverse logistics of lithium-based device batteries and is part of the research project “Hybride Lithiumgewinnung” from 2011 to 2013<sup>1</sup>. Especially logistical requirements and safety issues of battery recycling are discussed. In addition, technical and ecological constraints as well as regulatory frameworks for storage and handling of used lithium batteries are portrayed. To ensure the fulfilment of regulatory requirements, technical and organizational actions and personal behaviour of the participants need to be examined. The stated conditions are compared with the actual situation to determine the weak spots and to show the rooms for improvements.

**Keywords:** Reverse logistics, battery recycling, lithium ion battery, device batteries, battery collection.

## LOGISTYKA ZWROTNA BATERII LITOWYCH

**Streszczenie.** W Niemczech 15000 ton baterii corocznie podlega recyklingowi. Nowym wyzwaniem w tym zakresie jest wzrost liczby baterii litowych. Artykuł prezentuje problematykę związaną z recyklingiem baterii litowych na przykładzie wybranego programu w latach 2011-2013. W szczególności zaprezentowano wymagania dotyczące bezpieczeństwa i recyklingu. Dodatkowo, przedstawiono ekologiczne uwarunkowania i kwestie prawne dotyczące omawianych zagadnień.

**Słowa kluczowe:** logistyka zwrotna, recycling baterii, baterie litowo-jonowe, zbiórka baterii, baterie.

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## 1. Technical requirements for transport logistics

In 2011 more than 172 million lithium-based batteries have been sold in Germany, of which at least 35% need to be recycled according to German law (Batteriegelgesetz). The technical requirements for the transport of used batteries fall into the categories of collection, transition and storage. First safety issues are described.

### 1.1. Risks and threats of lithium-based device batteries

Over the last decade several fires as well as explosions have occurred while transporting used device batteries<sup>2</sup>. Especially internal or external inducted short circuits of lithium-based batteries have caused great damage<sup>3</sup>. Furthermore bursts, cracks, controlled and uncontrolled mechanical stress endanger a battery and can lead to highly exothermic reactions, due to the extreme energy density of lithium batteries. Yet, the most common transportation danger is an internal short circuit as a result of aging processes, humidity and temperature<sup>4</sup>.

Potential sources of risks appear in every process step of the reverse logistical chain. As a consequence every product on the German market comes with a safety datasheet published by the manufacturer, where the risks of fire and explosion are underlined:

“Unusual Fire and Explosion Hazards: Do not short circuit, recharge, over discharge (discharge below 0.0 Volts), puncture, crush or expose to temperatures above the maximum rated temperature as specified by the manufacturer cell may leak, vent, or explode. If a bright white flame is present, lithium content is exposed and on fire“<sup>5</sup>.

### 1.2. Collection

To fulfil regulatory requirements regarding the battery's collection, special repositories as well as transportation vehicles have to be used by all service providers and other actors in the reverse logistics chain of lithium-based batteries.

For instance, a service provider responsible for battery collection and transportation has to meet laws concerning transportation and has to be a professional company for waste disposal (§ 52 des Kreislaufwirtschafts- und Abfallgesetzes). This means that the partner is legally

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<sup>2</sup> Cf. Field (2009); unintended contact and penetration of moisture or water into a lithium-based accumulator or battery lead to a reaction with gas separation (e.g. hydrogen fluoride) in combination with a substantial volume growth.

<sup>3</sup> Cf. Gray (2010), p. 9; inner short circuit due to dendrite growth of Lithium at the anode.

<sup>4</sup> Cf. Boyle (2010), p. 18.

<sup>5</sup> S. Levis (2009), p. 2.

qualified to handle used batteries, whereby operations include the separate acquisition, treatment, recycling or disposal of wasted batteries<sup>6</sup>.

### 1.2.1. Collectionpoints

First and foremost consumers are in need of barrier- and fee-free access to collection points. The disposal of batteries should also be enabled free of certificates and other efforts at the following collection points:<sup>7</sup>

- Communal collection points like buyback centres
- Collection points of manufacturers and retailers
- Collection points of commercial waste management service providers dealing with wasted commercial and private batteries

Furthermore collection points have to be...

- widely and extensively present,
- arranged in a clean, appealing and weather-protected environment,
- equipped with numerous legally authorised collection boxes,
- equipped with information concerning the battery's collection and handling,
- reachable for suitable collection vehicles

to support a high collection rate as postulated in the Battery Law, supporting the demands of the German Recycling and Waste Act ("Kreislaufwirtschafts- und Abfallgesetzes")<sup>8</sup>.

Within this context it is for instance necessary to provide quartz sand to extinguish any fire of a higher amount of lithium-based device batteries, especially button cells. Flammable objects have to be removed from the battery's direct proximity and should be stored outside of the building.

To avoid potential short circuits of lithium-based device batteries, especially of batteries with a mass above 500 g, a simple tape on the contacts is sufficient. In addition, the assignment of skilled personal is necessary to increase safety.

### 1.2.2. Boxes

Battery containers can be divided into their main functions: Collection and transportation. Boxes used in the retail channel should be reasonably small, solid and reusable to meet the conditions at a retail checkout area. The relatively small boxes, called "Mini-BATT-Box" by

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<sup>6</sup> Cf. Bundesministerium der Justiz (08.11.2011a), §2 (17).

<sup>7</sup> For comparison see LAGA (2009), S. 16 and Bundesministerium der Justiz (08.11.2011b), §9 (3): „[...] No charges may be levied for returns to the collection points.“ [translated from German into English].

<sup>8</sup> Cf. Bundesministerium der Justiz (08.11.2011a), §2 (19), §16; Bundesministerium der Justiz (06.10.2011), §24.

the GRS Batterien, are made out of paperboard or plastics for a content about 5 kg wasted batteries and fulfil all stated requirements<sup>9</sup>.

Mini-Batt-Boxes can be depleted inexchangeable containers, like barrels (60 or 120 litressee. Fig. 1), for transportation and storage, keeping the batteries protected from variations in temperature or humidity. In addition they prevent the environment from leakage of battery fluid.



Fig. 1. Exchangeable boxes, containers and barrels for transportation

Rys. 1. Transportowe, wymienne pudełka, pojemniki i beczki

Source: SETON (2012); ERP Deutschland (2012); GRS Gemeinsames Rücknahmesystem Batterien (2012b), (2008a).

A paperboard-made box with the label “Used Lithium batteries” is applied for collection and transportation of up to 30 kg of batteries. Because these boxes can only be used once, they also have to be recycled properly. New boxes are distributed simultaneously with the collection. To reduce miss-sorting, the boxes are positioned in a manner that allows only small batteries to pass the slot of the box. Furthermore, suitable labelling allows the backtracking of misused boxes with non-desirable contents and initiates appropriate actions for preventions. Stability and all conditions of the packing instruction 903b of the ADR<sup>10</sup> have to be kept.

### 1.2.3. Collection vehicles

Vehicles used for battery collection by 3<sup>rd</sup> party providers have a permitted load weight between 3.5 t and 40 t. They differ from compacting, rotating drum, front- and rear-end loader vehicles for domestic waste collection<sup>11</sup>. The choice of vehicles complies with the subdivision of traffic into mere collection-traffic to the depot, mixed traffic or long distance traffic to the sorting or utilisation facility (see Table 1).

Collecting smaller amounts of batteries, like some hundreds of kilograms at one collection point, suits smaller vehicles, but depends on the pick-up cycle of the service provider. Overall small vehicles are often the best choice of for an urban environment. In contrast, long distance

<sup>9</sup> Cf. GRS Gemeinsames Rücknahmesystem Batterien (2011b), S. 15ff.

<sup>10</sup> Cf. Economic Commission for Europe Committee on Inland Transport (2012a), (2012b), pp. 34 and 163.

<sup>11</sup> Cf. Schwab (2007), S. 23ff.

transportation has to be efficient due to the high emergences of batteries<sup>12</sup>. Here the use of lorries is more suitable, since logistic depots, recycling centres and industrial establishments can be accessed with larger vehicles. In addition, numerous euro-pallets and barrels have to be loaded and unloaded in a short period of time. Moreover, many collection points can be served in one tour<sup>13</sup>.

Vehicles sizes for battery collection depend on following characteristics:

- quantity of batteries
- variety of batteries (mono charges, boxes, barrels, palletized or not)
- distance between collection point(s) and depot (length of tour)
- accessibility of collection point (inner city, recycling centres, industrial areas)
- other requirements (low-emission-zone<sup>14</sup>, badge obligation)
- carriage of loading equipment and the use of ramps

Table 1

Collection vehicles, transport quantities and areas of use (examples)

| Vehicle     | Permitted weight | Transp. quantity | Area of use   |
|-------------|------------------|------------------|---|
| transporter | up to 3,5 t      | ca. 1,4 t        | inner city, small quantity of batteries   |
| small lorry | 7,5 t to 12 t    | ca. 2,8 to 4,8 t | intermediate solution for a higher quantity of batteries in industrial areas and in commercial zones, for longer distances/ tours   |
| heavy lorry | up to 40,0 t     | up to 25,0 t     | long- distances with a high quantity of batteries, transportation from depots to sorting or utilization facilities, with more than 10 t per shipment according to the ADR |

Source: Own calculations.

Transportation vehicles have to stick to the Highway Code, especially with the proper securing of cargo, and to so-called ADR requirements applying the transport of dangerous goods, which also includes a proper skilled driver.

#### 1.2.4. Transition

The most crucial point within the reverse logistics chain of lithium-based device batteries, besides the physical transport itself, is the transition. Along with the filling of the boxes by the consumer and the transfer in suitable barrels for transportation, stacking the paperboard boxes

<sup>12</sup> Volume of shipments is up to roughly 25 t with 36 Boxes on one europalett and 26 europaletts per lorry.

<sup>13</sup> With a load capacity about 25 tonnes per lorry, one lorry is able to satisfy the battery collection of 290 collection points. With an average number of about 420 collection points per district (170.000 collection points apportioned to 402 districts), one lorry is enough to satisfy the battery collection of six districts per month. Own calculation, see GRS Gemeinsames Rücknahmesystem Batterien (2011a) in comparison to GRS Gemeinsames Rücknahmesystem Batterien (2011a).

<sup>14</sup> Cf. Pitschke (2011), S. 1f.; The use of low-emission vehicles, fulfilling all specifications of an low-emission-zone, holds a high potential for environmental relief.

and emptying boxes at a sorting facility puts physical stress to the batteries. Hence, control and avoidance of thermal and mechanical stress is very important at this step.

Besides thermal stress<sup>15</sup>, increased humidity has a high influence on the safety of lithium-based device batteries (and compounds of it). The higher the humidity, the higher the corrosion and the mechanical stress of a battery with all above mentioned effects<sup>16</sup>, so that the conditions of the direct ambience have to be considered within all reverse logistics steps.

Barrels with lithium-based batteries have to be treated in filled condition. Furthermore, button cells can be put on a backing film to prevent the metal tubings from contact and short circuits. Obviously, the choice of filling material depends on the composition of the lithium battery mix (button and round cells).

Safety measurements for composed loads have to be realised especially concerning the transition<sup>17</sup>. A solid ground, anti slip-mats, foiling and lashing of the cargo are some examples. In addition boxes and barrels have to be checked for leak-tightness and integrity.

#### *1.2.5. Storage*

If the quantity is too low for a direct transport from the collection point to a sorting facility, an interim storage of battery mixes including lithium-based device batteries is necessary. Furthermore, storing batteries near the sorting facility is possible.

In general block-, ground- or even high-bay-storage are feasible options. Yet, most often ground-storage is used for batteries. Four to six barrels fixed on euro-pallets are usually stacked twice (depending on the barrels' stability and design). Furthermore, paper board boxes have to be foiled on euro-pallets. Depending on their stableness and their base-layer-arrangement, euro-pallets with paper-board boxes can also be stacked twice.

During storage it is sometimes necessary to consolidate smaller quantities of batteries from not completely filled boxes or barrels. Prior to transportation, it is essential to check all barrels for their filling level and sealing. Defects or instabilities are prohibited<sup>18</sup>.

Environmental aspects (temperature and humidity) are relevant as well. Applicable documents, battery safety data sheets, regarding technical requirements are available for every lithium-based device battery on the market. For instance, the data sheet for a LiMnO<sub>2</sub>-Batterie indicates: No temperatures above 30°C and no temperature fluctuations are allowed; the battery has to be stored away from heating elements and has to be protected from direct

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<sup>15</sup> Cf. Otsuki und Ogino (2009), S. 284f.; self-warming occurs with temperatures up to 350°C.

<sup>16</sup> Cf. Jennings und Kiedrowski (2009), S. 824ff; Field (2009).

<sup>17</sup> Cf. Proper securing of the cargo according to Bundesministerium für Verkehr, Bau und Stadtentwicklung (04.12.2010), §22, in combination with technical standards: VDI-Gesellschaft Produktion und Logistik. See for further reading: Sander (2003).

<sup>18</sup> Cf. Bundesanzeiger, S. 4.1.1ff.

insolation<sup>19</sup>. However, statements regarding common safety standards like occupational or fire regulations are not in the scope of this study.

## 2. Ecological requirements for reverse logistics

Lithium-based battery recycling contributes to environmental protection and saves resources for more sustainability<sup>20</sup>. As a result of that, all necessary processes along the battery disposal logistics system have to be tested for their environmental demands, to avoid additional environmental pollution<sup>21</sup>. The focus is on transportation with interim storage and collection, respectively. The sorting facility bears the responsibility for an environmentally friendly battery sorting (see chapter 0). A complete analysis in form of an eco-report is not a part of the study due to its extent, but it is noteworthy regarding the complex coherences.

The implementation and supervision of ecological needs are a main part of the organisational demands, their structure and the personal behaviour of all participants.

### 2.1. Transportation

A transport, irrespective of different transportation modes, is a burden for the environment and should therefore be reduced to a minimum. Every distance covered should be as short as possible. Trucks and other vehicles should also comply with the latest technological progress to reduce carbon dioxide emission as much as possible<sup>22</sup>.

Because of the wide spread collection points (Fig. 2) suitable touring software is necessitated and the amount of collected batteries should also be collected in a sequence that diminishes the transport not only economically, but also ecologically.

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<sup>19</sup> Cf. VARTA (2004), S. 5.

<sup>20</sup> Cf. Bundesministerium der Justiz (06.10.2011), §1.

<sup>21</sup> Cf. European Portable Battery Association (2004), S. 10.

<sup>22</sup> Cf. Cordwell-Smith (2001), S. 12f.; 95 Millions of tonne-kilometres and 1.5 millions of litres of fuel EU-wide for battery collection in the year 2000.

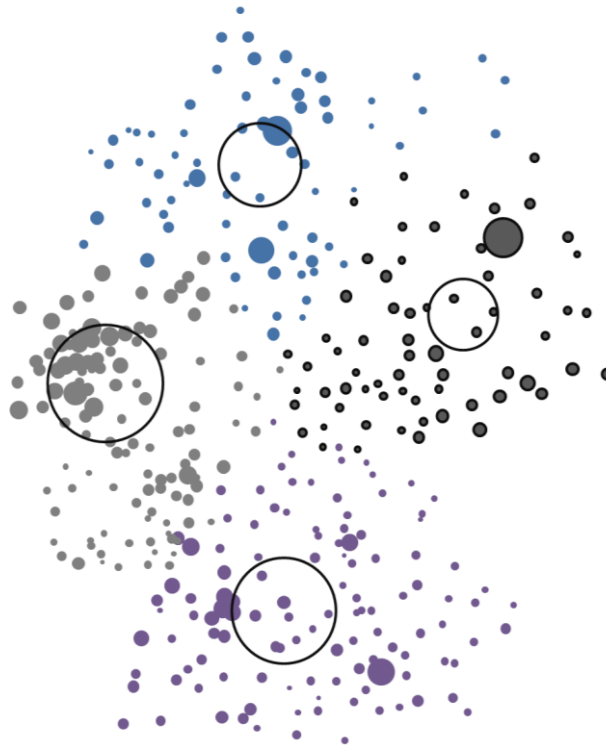


Fig. 2. Aggregated collection points and four centers of gravity<sup>23</sup>  
 Rys. 2. Punkty zbiorcze i cztery centra lokalizacji recyklingu

Returnable boxes and barrels ought to be preferred to one way containers, to reduce the environmental burden from their production disposal. If one way containers are inevitable, they should be made of recyclable materials. It is important that containers for collection and transportation are lightweight. Foldable containers are advantageous for empty runs, because they are stackable and have low space requirements.

## 2.2. Collection point / storage

Regarding storage, base area and energy requirements are most important for the ecological compatibility of transport logistics. Increasing requirements lead to rising negative effects to the environment. All negative influences should be minimised and depositories have to be embellished according to ecological matters. Examples are warehouses with a rare need for relocation (of the batteries), little internal traffic and energy-efficient building measures<sup>24</sup>.

<sup>23</sup> Circles diameters represent the quantity of batteries according to the number of inhabitants, Statistische Ämter des Bundes und der Länder (2012), and their collected batteries (e.g. in Berlin that is 100 to 135 g collected batteries per inhabitant), GRS Gemeinsames Rücknahmesystem Batterien (2010a).

<sup>24</sup> A long-term storage was not object of the investigation “Hybride Lithiumgewinnung” due to the focus on recovering lithium.



### 3. Framework of the organisation

Aside from the forecited technological and ecological exigencies of reverse transport logistics, some organisational frameworks and control mechanism have to be established. Due to the comprehensive collection (from wide spread collection points) a central organisation is necessary, fulfilling the following functions:

- control of battery logistics system by delegating tasks to service providers
- verification of efficiency, geographical coverage and stability
- development and optimisation of the systems' processes
- role as mediator between all involved partners, enterprises and the public
- balance of risks of the disposal logistics in case of a local service failure

Due to the geographical coverage of the batteries' occurrence, especially local service providers are suitable for the collection. They can use nearby depots and have close contact to collection points. Using only one 3<sup>rd</sup> party logistic provider for all federal states in Germany would lead to an isolated disposal logistics network with specialising in batteries, but without using synergy effects through resource pooling with other existing recycling networks<sup>25</sup>.

A central organisation grants planning reliability by contracting service partners for a predefined period of time while it also ensures security of supply for the sorting factories. A potential loss of a single service provider can be compensated by the central organisation through contracting an adjacent service partner. As a result, the total system is more stable at all times.

A central organisation also generates a constructive competition based on standardized performance requirements and transparency which is useful for federal-wide accounting with battery producers, too. In this case, some data has to be collected and analysed according to the success monitoring called "Erfolgskontrolle" of the German battery law (BattG).

The organisation of the battery disposal logistics system has to define verifiable safety standards especially for lithium-based batteries. These standards have to be reviewed and revised frequently. Examples are the standardised transport, collection containers and the co-operation of service partners in general.

There are additional claims concerning service providers and other parties within the reverse logistics chain. For example requirements like a certified waste management company ("Entsorgungsfachbetrieb")<sup>26</sup>, internal and external quality controls and communication standards for the parties involved.

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<sup>25</sup> Resources are personnel, vehicles, storage space and combined tours with other substances.

<sup>26</sup> Cf. Bundesministerium der Justiz (06.10.2011), §52.

## 4. Sorting requirements

Sorting, as a further part of the recycling process and the take-back system in general, has to meet certain standards, similar to the demands of the transport logistics (e.g.) concerning the transportation containers.

A steady supply with spent batteries is necessary for an economical sorting process. In addition a sufficient storage space should be provided. A strict incoming goods inspection is essential to secure containers realised as half-filled or filled with mainly lithium-based batteries each above 500 g. In practice, these inspections are applied through scanning barcodes or reading delivery notes placed on collection containers or the whole euro-pallet. The content of battery collection boxes and barrels is often checked at random. A forklift empties the collection containers on top of a band-conveyor, where the manual sorting takes place. Trained personal is necessary for this purpose to identify and reject contents harmful to the sorting process. Furthermore, a separation of possibly leaked substances like alkaline solutions or the batteries' electrolytes is mandatory.

Lithium-based button-cells are a safety risk for the sorting process due to their electrically conductive surface. As during transportation, batteries are often in motion in the sorting process. The reaction-delay after a movement-induced short circuit has to be concerned. High temperatures occur after a remarkable amount of time and are capable causing fire or even explosions. As a result, all containers have to be supervised and unauthorised personal has to be kept away. Early detection and removal of highly charged lithium-based device batteries can lower the risk of sorting, too.

Batteries for the sorting process have to be carried in suitable containers, preferably in the collection and transport boxes or barrels; while other sorts of containers can be used during the sorting process itself, such as big bags, mesh boxes laid-out with a foil and metal boxes.

Arrangements for fire fighting and fire prevention have to be provided as well as personal familiar with occupational-safety measures. In practice, this is generally assured and reviewed by regular quality control.

In summary, the process of sorting lithium-based device batteries with a manual pre-sorting and a (semi-) automated sorting<sup>27</sup> should fulfil the following conditions:

- avoidance of excessive mechanical and thermal stress
- avoidance and prevention of short circuits by using separating materials, non-conductive equipment and suitable containers
- differentiation of lithium-based batteries from others (fractionation)
- use of automated detection/sorting methods (X-ray, UV light)<sup>28</sup>

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<sup>27</sup> Cf. UNI-CYC GmbH (2001a); UNI-CYC GmbH (2001b); Flow chart of the sorting process.

<sup>28</sup> The detection method discerns nowadays in primary and secondary lithium-based batteries, but not in further chemical constituents as evaluated in "Typology of lithium-based device batteries" as one part of the project "HybrideLithiumgewinnung".

- cover lithium-based batteries with quartz sand layer by layer
- labelling of fractions already sorted
- storing of returnable barrels and disposal of one-way containers
- opportunity to separate liquid residuals (acids) before sorting
- opportunity to filter barrels filled with quartz sand
- skilled personal, occupational-safety and fire-preventing measurements
- ability to adopt the sorting process for new battery fractions<sup>29</sup>

#### 4.1. Recycling performance of lithium based device batteries

The battery recycling performance depends on the collection, sorting and deployment rate. Today, the collection rate is 44% for all used batteries in Germany (Fig. 3),<sup>30</sup> complying with the determined rate for 2012 (35%) and almost even with the aspired rate for 2016 (45%)<sup>31</sup>.

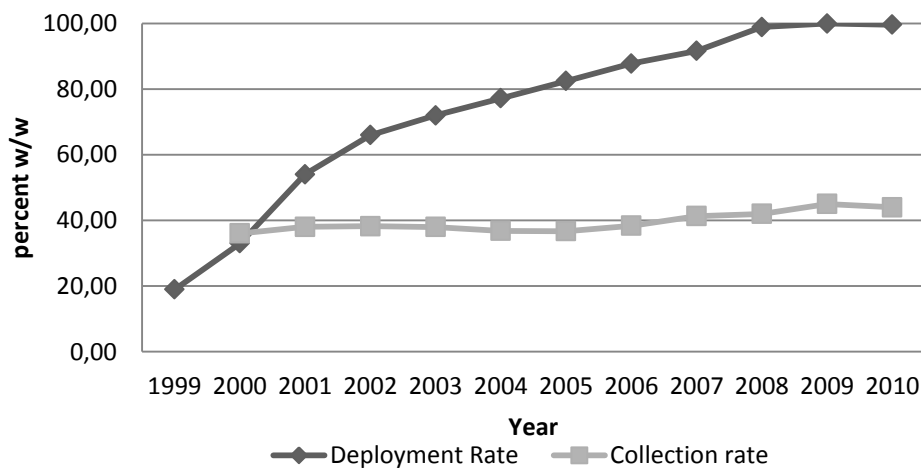


Fig. 3. Utilisation and collection rate of device Batteries - 1999 to 2010<sup>32</sup>  
Rys. 3. Utylizacja i zbiórka baterii w latach 1999-2010

The collection rate shows a slight increase over the last decade, while the deployment rate rose remarkably. Nowadays, nearly 99.6% of all sorted batteries are deployed, i.e. only 0.4% have to be disposed as “[...] lithium-primary batteries, with no possibilities of recycling [...]”<sup>33</sup>. That correlates with the deployment rate of 81% for lithium-based device batteries. This rate is solely based on lithium-based button cells in a battery mix with aluminium-

<sup>29</sup> Cf. GRS Gemeinsames Rücknahmesystem Batterien (2010b); Classification of masses. Cf. Bundesministerium der Justiz (08.11.2011a), §15 (7); Sorting according to chemical constituents.

<sup>30</sup> Cf. GRS Gemeinsames Rücknahmesystem Batterien (2011a), S. 5.

<sup>31</sup> Cf. For further reading of recycling rates see: Schmidt (2006).

<sup>32</sup> Cf. Schmidt (2006), (2005); GRS Gemeinsames Rücknahmesystem Batterien (2011a), (2010a), (2009), (2008b), (2007a), (2007b), (2006), (2005), (2004).

<sup>33</sup> S. GRS Gemeinsames Rücknahmesystem Batterien (2011a), S. 8.

manganese, silver-oxide and zinc-air batteries<sup>34</sup>. Roughly 33% of that battery mix consists of lithium-based batteries, because this ratio correlates with the ratio of sold lithium-based button cells to all button cells. The sorting rate for all batteries is at least 98%<sup>35</sup>.

By applying the calculation rules for collection rate according to the German battery law (BattG), the collection rate for lithium-based device batteries is very low from 2001 to 2010. After a rate of 22%, only 9% are achieved today. The reason is a boost in sales volume (+800 %) of lithium-based device batteries, especially of round cells, while the amount of collected lithium-based batteries increased by 150 % (Fig. 4).

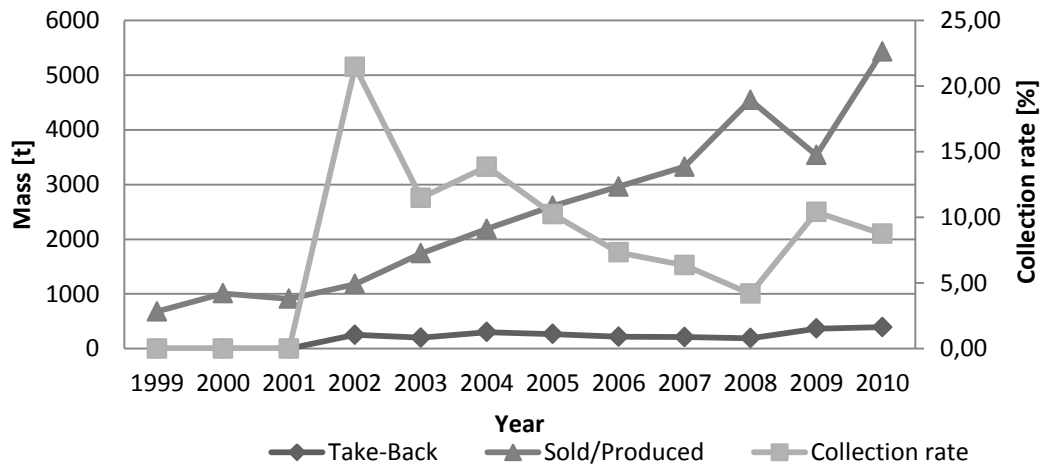


Fig. 4. Collection rate of lithium-based device batteries - 1999 to 2010<sup>36</sup>  
Rys. 4. Zbiórka baterii litowych w latach 1999-2010

The recycling performance, as a product of collection, sorting and deployment rate<sup>37</sup>, is 41%<sup>38</sup> for all types of used batteries in 2010. Regarding lithium-based batteries, the recycling performance is between 6.4% (round cells) and 10.7% (button cells) or 7% for all lithium based batteries, respectively (Table 2).

<sup>34</sup> Cf. GRS Gemeinsames Rücknahmesystem Batterien (2011a), S. 13; 86 t primary button cells collected in a battery mix with 202 t button cells.

<sup>35</sup> Cf. GRS Gemeinsames Rücknahmesystem Batterien (2007a), S. 19; Sorting purity.

<sup>36</sup> Cf. Schmidt (2006), (2005); GRS Gemeinsames Rücknahmesystem Batterien (2011a), (2010a), (2009), (2008b), (2007a), (2007b), (2006), (2005), (2004).

<sup>37</sup> Cf. Bundesministerium der Justiz (08.11.2011a), §15 (1) in Verbindung mit §2 (20).

<sup>38</sup> Recycling performance device batteries:  $(44 \times 98 \times 94,7) \% = 40,83 \%$ .

Table 2

## Recycling performance in comparison (based on 2010)

| (2010)                 | Collection rate<br>[%] | Sorting rate<br>[%] | Deployment rate [%] | Recycling<br>performance [%] |
|------------------------|------------------------|---------------------|---------------------|------------------------------|
| batteries in general   | 44,00                  | 98,00               | 94,70               | 40,83                        |
| Li/Li-Ion button cells | 13,78 <sup>39</sup>    | 98,00               | 79,45 <sup>40</sup> | 10,73                        |
| Li/Li-Ion round cells  | 7,42 <sup>41</sup>     | 98,00               | 88,44 <sup>42</sup> | 6,43                         |
| Li/Li-Ion total        | 8,74 <sup>43</sup>     | 98,00               | 81,00 <sup>44</sup> | 6,94                         |

Source: Own calculation despite of: Sorting rate and collection rate in general cf. GRS Gemeinsames Rücknahmesystem Batterien (2011a, S. 14f).

Compared to paper collection, which started in the 1970s, taking about 40 years to rise its nowadays high recycling performance, it will certainly take many more years to establish a battery recycling system with an equally high recycling performance<sup>45</sup>.

For sustainable and economic recycling of lithium-based device batteries, a rise of the recycling performance is inevitable. Primarily, this can be achieved by improving the collection rate with the help of a new concept of a battery disposal logistics system<sup>46</sup>.

## 5. Target-performance comparison of the basic conditions (requirements)

The portrayed fundamental requirements especially for transportation in a battery reverse logistics, with all its technical, organizational and legal components, have to be compared with the actual situation. The German take-back system for batteries, the foundation GRS-Batterien, serves as benchmark, since it has a market share of 85% in Germany<sup>47</sup>.

The requirements are summarized in Table 3, comparing all requirements directly to their implementation. Deficits are emphasised and possibilities for improvements are shown.

<sup>39</sup> Calculation: In the year 2010 the Li-button-cells taken back as a 33-percent 87 t buttoncell-battery mix with 202 t placed on the market:  $87 \text{ t} / 202 \text{ t} \times 33 \% = 13,78\%$ .

<sup>40</sup> Calculation: 16 t of 73 t not utilized.

<sup>41</sup> Calculation:  $392 \text{ t collected Lithium-round-cells} / 5.278 \text{ t Li-round-cells placed on the market} = 7,42\%$ .

<sup>42</sup> Calculation: 61 t of 392 t Li/Li-Ion not utilised.

<sup>43</sup> Calculation:  $479 \text{ t} / 5.480 \text{ t} = 8,74\%$ .

<sup>44</sup> Calculation: 331 t Li/Li-Ion round-cells and about 59 t Li-Li-Ion button-cells are utilized from 479 t collected Lithium-based batteries.

<sup>45</sup> Cf. Mulhaupt und Plümer (1990).

<sup>46</sup> A new concept of a battery disposal logistics system was one of the main achievements of the project "Hybride Lithiumgewinnung".

<sup>47</sup> Used for analysing battery take-back systems according to the project.

Table 3

## Technical requirements for a battery disposal logistics system

| <b>Technical requirements</b>         |   |
|---------------------------------------|---|
| <b>Collection/<br/>Transportation</b> |   |
| Collection point                      | accessibility; free of charge; nationwide; sufficient number of functional containers; information concerning the collection; trained staff   |
| collection and transport container    | differentiation between collection and collection with transportation; protection from heat, humidity, temperature changes and leaking; possibility of decantation; closable and stackable containers, mail-ordered boxes for the initial equipment; information material   |
| Vehicles                              | types of vehicles have to meet the collection points' accessibility and transport requirements (long and short distance); adherence of national road traffic regulations (StVZO); possibility of cargo securing (lashing points etc.) and transportation of dangerous goods; transportation capacity of 1.5 tonnes to 21 tonnes, ADR-skilled driver   |
| <b>Transition</b>                     | moving of containers for collection and transportation just completely filled, otherwise use of filling material; prevention of high mechanic or thermal stress (use of suitable forklifts); securing of cargo; check for damage  |
| <b>(Short-time)<br/>Storage</b>       | possibility to consolidate little quantities of batteries to larger quantities with avoidance of short circuits; protection from heat, humidity, temperature changes and leaking, temperatures up to 30°C as optimum, maximum stacking factor of two; adherence of safety rules, like employment protection and fire protection   |
| <b>Sorting</b>                        | avoidance of humidity, unusually high mechanic or thermal stress and short circuits by using separator materials and non-conductive tools and containers; differentiation of lithium-based and other device batteries (fractionation); use of automated detection methods (like the x-ray detection) <sup>48</sup> ; quartz sand coverage of batteries (in layers); labeling of sorted fractions; preparation of reusable and disposal of single-use containers; possibility to separate liquid residuals before sorting; possibilities to filter barrels filled with quartz sand; skilled personal, employment and fire protection measurements; ability to adopt the sorting process for new battery fractions <sup>49</sup> ; recognition and separation of high-charged batteries |

### 5.1. Collection and transportation

Today's collection of lithium-based device batteries already fulfils most of the specified requirements. Especially the numerous collection points lead to comprehensively high collection rates. Due to legal regulations for a battery take-back, every store opening adds a collection point equipped with take-back boxes.

Typically all battery boxes in Germany meet the requirements for wasted batteries and lithium-based batteries up to 4 kg. However, for the collection of obviously defect batteries, irrespective of their chemical system, no legal regulations or usable containers are available, because of a lack of legal standards, particularly for the definition of a defect battery.

<sup>48</sup> The detection method discerns nowadays in primary and secondary lithium-based batteries, but not in further chemical constituents as evaluated in "Typology of lithium-based device batteries"

<sup>49</sup> Cf. GRS Gemeinsames Rücknahmesystem Batterien (2010b); Weightcategories. Cf. Bundesministerium der Justiz (08.11.2011a), §15 (7); Sorting according to chemical constituents.

The insertion slot of today used boxes made out of paperboard or plastics is not able to prevent impurities like condensators, needles and pins (hospital collection), so called do-it-yourself-batteries<sup>50</sup> and other garbage. Furthermore the aspect of a cost-free collection contributes to the fact that personell/staff at collection points doesn't see them self responsible for the correct disposal in collection boxes. They only follow legal regulations (e.g. providing space in the store for the collection box). This problem causes false installation of boxes which no longer fulfil stability requirements, especially in transport.

Due to practical considerations 120 l barrels are gradually replaced by 60 l barrels. A separate collection box for lithium-based batteries is used to collect e-bike batteries and other lithium-based device batteries over 500 g at specialised bicycle dealers. Yet, the box itself is identical, except of a label pointing out the lithium content and that batteries' contacts have to be isolated with tape. Those boxes don't allow the inflation with other batteries, enabling an adequate handling of their contents<sup>51</sup>.

In general the appointment of skilled personnel is implemented appropriately. Nevertheless the regulations imply an additional effort for the staff, which lowers its motivation to obtain all stated conditions.

Used Lithium-based batteries are often stored in little quantities near the entrance or the checkpoint areas. Higher quantities of batteries are stored in the retailer's depot and even larger quantities outside in a separate storing area (e.g. near the loading ramp) or in the depot of the region. Typical problems that occur are half-filled collection containers, inadequate stacked boxes or barrels and influence of direct sunlight or rain. Especially rain and humidity can cause short circuits (with all above mentioned effects and lead to formation of acids, which are an avoidable threat to the environment.

Public-law disposal companies receive high quantities of used batteries, which are stored 60 l barrels. Rain and other environmental influences make collection boxes age much faster. The content gets in contact with humidity and alkaline compounds or other deleterious solutions, whose leakage has to be avoided. Furthermore, these solutions complicate the sorting process, because they have to be skimmed and disposed separately, resulting in avoidable costs.

The accessibility of the certain collection point, as a function of the vehicle's size, is assured by the service partner obeying economical interests.

Potential deficiencies of service providers are identified during the assessments by the take-back organization. Hence, counteractions can be initiated. Sometimes, e.g. there is a lack of load securing during transportation, a poor acquisition check of boxes and barrels at the collection point and missing sufficient information about appropriate actions in the case of

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<sup>50</sup> Do-it-yourself-batteries are soldered lithium-based cells, taken from battery packs in the context of repairing a battery or changing their performance. Because of a lack of labelling, the do-it-yourself-batteries (all cells are just in one color without a print) in combination with bare wires and high energy densities lead to an abnormal high risk of short circuits and fire.

<sup>51</sup> Cf. GRS Gemeinsames Rücknahmesystem Batterien (2012a).

impending dangerous situations. Sometimes even an appropriate extinguishing system for lithium-based batteries is missing.

## 5.2. Transition

As illustrated before, the transition of the batteries abets short circuits through additional movement of the containers. Fortunately, threat-reducing conditions are already applied. Service providers use suitable forklift trucks with gripping devices that handle the barrels without significant squeezing and treat palletized boxes manually.

Suitable security measures are used during transportation with special auxiliary materials. Nevertheless, potential for improvement exists. Separating lithium-based batteries from the battery mix ahead of sorting, for example through separate collection at the same collection-points, is only partly practised. This is because of a lack of experience; although most of the requirements of transportation and transition are already regulated by law. Furthermore, all collection boxes and barrels should be tested for possibilities to increase safety.

## 5.3. Storage

The storage of lithium-based device batteries is carried out at retail store collection points, in depots of service providers and local public collection stations, the sorting plant and the deployment plant.

Sorting and deployment plants handles lithium-based batteries best, due to the distinctive safety and risk awareness of all actors. At these places lithium-based batteries are not only treated in mixes of batteries, but also as mono-fractions (with a higher risk potential). Especially appropriate extinguishing systems like quartz sand to dam up and fighting a fire caused by a lithium-based battery is crucial at this point of the disposal logistics system. In addition, the skilled personnel contribute to the protection of the environment.

The cost-free take-back of batteries leading to the mentioned fact of inexperienced personal or a low awareness of the dangers associated with lithium-based device batteries, storage in the retail channel and at public disposal companies has a higher hazard potential.

## 5.4. Sorting

The up-to-date sorting of lithium-based device batteries fulfils most of the a forementioned conditions. Worthy of mention is the high sorting rate of about 98%. Deficits are located in recognising potentially dangerous batteries on the basis of their state of charge. Furthermore, only lithium-based primary and secondary round cells can be differentiated, but lithium-based button cells are sorted in a mix containing other button cells. There is no



separation according to the exact chemical system of a lithium-based battery, impeding additional utilisation possibilities of contained raw materials<sup>52</sup>.

## 5.5. Ecology

Environmental burdens of the recycling of lithium-based device batteries are considered in economically planned transports. With the help of route planning, the collection process can be performed in a cost-minimal way. Usually, the shortest way is not only the cheapest, it also leads to the lowest ecological impact through emissions<sup>53</sup>.

Other ecological requirements (s.

Table 4), for example the use of modern vehicles, energy efficient buildings, sorting and treatment processes are implemented, as long as they are economically acceptable<sup>54</sup>.

Table 4

Ecological requirements for a lithium-based battery disposal logistics system

| <b>Ecological requirements</b> |  |
|--------------------------------|--|
| Transportation/<br>Boxes       | latest technological progress, low-emission vehicles; suitable touring software for minimized distances; combined collection to use long-distance transportation; low-weighted, sustainable, recyclable, stackable, closable and leak proofed containers |
| Collection points/<br>Storage  | Optimising space and energy requirements; avoidance of unneeded transshipping; safety-measurements against leaching to groundwater (acids out of defect barrels)   |

## 5.6. Organisation

Established battery take-back systems satisfy all described exigencies concerning monitoring and controlling of the logistics chain (Table 5). The specific hazard of lithium-based batteries is reviewed by specialist's forums and working groups<sup>55</sup>. The question raises, how the legal framework should be interpreted and extended, for example the ADR and its requirements concerning battery mixes with a higher share or a higher quantity of lithium-based device batteries in a possible future.

<sup>52</sup> Cf. Umicore Battery Recycling (2010); especially cobalt-rich secondary lithium batteries enjoy a consistently strong demand for a rentable utilisation (processes designed only for cobalt extraction).

<sup>53</sup> Cf. Cordwell-Smith (2001); transport distances in the recycling.

<sup>54</sup> For a detailed statement it is necessary to examine a particular take-back system for batteries with all its actors and logistic processes. That was no part of the project.

<sup>55</sup> Cf. GRS Gemeinsames Rücknahmesystem Batterien (2012c); G<sup>2</sup> Forum. Cf. GRS Gemeinsames Rücknahmesystem Batterien (2012a); In collaboration with Zweirad-Industrie-Verband (ZVI).

Table 5

## Organisational requirements

| <b>organisational requirements</b> |   |
|------------------------------------|---|
| Take-back system                   | Controlling of the reverse logistics network (especially according to a high rate of efficiency); continuous evolution of the processes; Data-mining and evaluation according to the collection, sorting and utilization processes; role as a mediator (sub-contractors, service partners); risk-balancing in the case of a service partners' breakdown; determination of standards especially according to safety and container management |
| Service partners                   | requirements according to the battery law, as certified company for battery recycling   |

A monitoring of the organisation's efficiency and its area covered by the battery disposal system is executed every year with a verification of success ("Erfolgskontrolle"). Competitiveness and efficiency is ensured by periodical open competitive bidding for all logistics parts of the battery recycling<sup>56</sup>.

## 6. Conclusion of target-performance comparison

Despite sporadic deficits of the collection, the transition and the storage of lithium-based batteries, the bigger part of all described technical, ecological and organizational requirements are sufficiently fulfilled. Every logistics process has to undergo further improvements, to cope with the projected higher share of lithium-based device batteries. Further assessment of collection and transportation containers according to the specific requirements of lithium-based device batteries should be performed perpetually. Protection from environmental influences and leakage of highly flammable liquid organic electrolytes are some of those issues. An improved slot design of the battery collection boxes in combination with more motivated personal can help to reduce impurities. The latter would also lead to a better preparation of transports.

A periodical check of control mechanisms and organisational structures of a battery take-back system induces a higher and robust collection rate. The quality of the battery mix including lithium-based batteries defines the value of secondary raw materials after treatment<sup>57</sup>.

<sup>56</sup> Cf. Bundesministerium der Justiz (08.11.2011a) §§ 6 (6) und 15 (1).

<sup>57</sup> Mercury impurities lead to higher processing costs and to a low value of the secondary raw materials.

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## Omówienie

W artykule przedstawiono kwestię recyklingu baterii litowych wykorzystywanych w sprzętach domowego użytku w Niemczech. Omówiono kwestie ekologiczne, uwarunkowania prawne i przede wszystkim wymagania logistyczno-organizacyjne systemu zbiórki tego rodzaju baterii.