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Recycling options for disposable and rechargeable dry-cell batteries in Ghana and Egypt

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Egypt

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Ghana

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%	Percent
a.k.a.	also known as
EEE	Electrical and electronic equipment
EoL	End of life
g	gram
GDP	Gross domestic product
kg	kilogram
LIB	Lithium ion battery, also Li-Ion
LIB-polymer	Lithium-ion polymer battery
Li-Ion	Lithium-ion battery, also LIB
Li-M	Lithium-manganese-dioxide battery
$LiSO_2$	Lithium sulfur dioxide
MnO_2	Lithium-manganese-dioxide battery (or)
NiCd	Nickel-cadmium battery
NiMH	Nickel-metal hydride battery
NiZn	nickel zinc battery
PC	Personal computer
POM	put on the market
t	metric tonne (1000kg)
WEEE	Waste electrical and electronic equipment

1. Introduction

As part of the project "Global circular economy of strategic metals – best-of-two-worlds approach (Bo2W)", the following document presents research into disposable and rechargeable non-lead dry-cell battery recycling in the project pilot countries Ghana and Egypt.

Non-lead dry-cell batteries are commonly used in many applications. Yet these batteries contain materials that are hazardous to humans and the environment if not properly handled. Legislation in the EU and from many other governing bodies regulates batteries' safe disposal. Many countries have found recycling to be one effective way to manage the risks associated with waste-disposal leaks while also reusing the material resources the waste contains.

After defining the scope and main applications for batteries in Section 2, this report presents the health and evironmental risks associated with non-lead dry-cell batteries in Section 3. The subsequent Section 4 describes common recycling methods used for the majority of non-lead dry-cell batteries. Then, European and particularly German battery collection regulations, processes and rates are summarised in Section 5 to offer cost estimates for battery recycling. These figures are used in Section 65.3 to estimate amounts and disposal costs for batteries in the Bo2W project's two pilot countries Egypt and Ghana. Battery disposal experiences from these two pilot countries are also described.

Based on the analysis and experiences reviewed in earlier chapters, Section 7 presents the report's proposed disposal options for batteries: either in municipal waste or recycled in special centres. Section 8 lastly explains the conclusions drawn from the research and describes which proposed disposal option is most recommendable for the pilot countries.

2. Dry-cell battery specifications and recycling methods

This study covers all **non-lead dry-cell batteries**, which shall hereafter simply be referred to as "batteries". Included in the study are disposable (a.k.a. "primary") and rechargeable (a.k.a. "secondary", "accumulators") batteries. Table 1 offers a list of the most common non-lead dry-cell battery types, also shown in Figure 1 below.

Table 1: Most relevant non-lead dry-cell batteries included in this study

- nickel-cadmium (NiCd)
- nickel-metal hydride (NiMH)
- nickel zinc (NiZn)
- lithium-ion and lithium-ion polymer (Li-Ion, LIB and LIB-polymer)
- lithium manganese dioxide (MnO_2 or Li-M), also as button cell
- lithium sulfur dioxide ($LiSO_2$)
- zinc-carbon and zinc-chloride
- alkaline-manganese, also as button cell
- zinc air
- silver oxide (button cell)

These batteries are generally **portable** and weigh under one kilogram, such as button cells and the various AA, AAA and AAAA formats. Laptops, tablets and other WEEE often contain dry-cells, like Li-ion and LIB-polymer batteries. Hybrid cars also increasingly employ Li-ion batteries; however, these are not included in this study. The same applies for lead-acid batteries.

Figure 1: Sampling of non-lead dry-cell batteries included in this study

Source: Oeko-Institut

Batteries of all types, including non-lead dry-cell batteries, are typically **listed as hazardous waste** because of the fire hazards and health and environmental risks linked to their metal content. (See Section 3 for more details.) Proper processing, particularly of EoL batteries, ensures that this waste does not hurt humans or the environment. In Europe, such waste management has been addressed for many years by legal requirements to contain hazardous waste and is increasingly of interest as part of initiatives to transform perceptions toward seeing all waste forms as valuable resources for a circular economy. Like many wastes, batteries contain materials that are valuable, such as:

- Ferromanganese concentrate,
- Cadmium (Cd),
- Copper (Cu),
- Graphite,
- Lead (Pb),
- Manganese (Mn),
- Mercury (Hg),
- Nickel (Ni),
- Potassium (K),
- Silver (Ag),
- Steel,
- Zinc concentrate (Zn),
- Paper, and
- Plastics: PVC, Nylon, etc.

Since these batteries are increasingly used in a **wide range of applications**, monitoring safe disposal is crucial. The applications in Table 2 below often contain various battery types with weights in the specified ranges.

Table 2: Estimated battery weights (g) and lifetimes (yrs) per battery-containing device

Battery-containing device	Battery types	Estimated weight range per battery unit (g)	Estimated lifetime range (years)
Cameras	Lithium button, Li-ion, NiMH, alkaline-manganese, silver-oxide, NiCd	Non-buttons <100g	1-10
Clocks/ radios	Alkaline manganse, Li-ion, lithium button, NiCd	Buttons or non-buttons <100g	1-10
Desktop computers	Li-M button, Li-ion,	Buttons (<5g, average 3g)	5-10
Laptop computers and tablet PCs (often containing a button and a non-button battery)	Li-M, Li-ion, Li-ion polymer	Buttons (<5g) and non-buttons 300-500g (average 400g)	2-10
MP3 players	Lithium button, alkaline batteries	Buttons or non-buttons <100g	1-5
Power tools	NiCd	Non-buttons 300g - 2 000g	0.2-10
Telephones: mobiles, smartphones, cordless phones	Li-ion polymer, Li-ion, NiMH	Non-buttons 20g - 50g (average 30g)	2-8
Torches	Button, alkaline, zinc-carbon	Buttons (<5g) or non-buttons 30g - 500g	0.2-5
Watches/ calculators	Li-M, lithium buttons, silver-oxide	Buttons or non-buttons <100g	1-10
Other: toys, medical devices, remote controls, automotive, eBikes, etc.	Alkaline-manganese, Li-M, NiCd, Li-ion, NiMH	Buttons or non-buttons of all weights	1-10

Source: Oeko-Institut compilation from [Buchmann 2015, Bo2W 2012-15, EC 2011, GRS 2007, Mills 2014]

A **battery's lifetime** differs per type and environment. Particularly for the many rechargeable battery types, factors such as how discharged the battery is before recharging, the number of charging cycles and how much it has been overcharged also impact lifetime. Environmental temperature can also affect the lifetime of all battery types. Table 2 also shows the conservatively estimated average lifetimes for batteries used in specific applications in Egypt and Ghana. Real figures may differ because of unpredictable weather and storage conditions.

Under EU initiatives, understanding which products contain batteries has been an initial step in consumer awareness to promote collection initiatives and properly dispose of EoL batteries. Municipalities follow one of two common methods for responsibly disposing of batteries. They collect batteries either in general municipal waste or separately for recycling.

3. Health and environmental concerns associated with dry-cell batteries

The EU lists many non-lead dry-cell battery types as **hazardous waste** because they contain **mercury, cadmium, lithium** or **other metals** hazardous to human health and the environment when improperly handled.[1] The European Environment Agency and the US Environmental Protection Agency, among other organizations, recognise these metals as toxic substances that can have severe human health effects (ex. on lungs and kidneys and are generally carcinogenic) and can accumulate in the food-chain (biomagnification). Though when properly contained in batteries, these substances pose only limited risks; however, damaged batteries can leak their contents and improper handling and storage can also increase the risks of fire.

Since the EU's Battery Directive took effect in 2009, many **cadmium-containing batteries** were replaced on the market by batteries with lower amounts of less hazardous metals, which may be disposed of in general municipal waste. While some studies indicate that this Directive reduced the volume of cadmium entering EU and US waste disposal systems between 1990 and 2010 by 60% [EEA 2012], many older, cadmium-containing dry-cell batteries, which are still in use, require proper handling and disposal. As well, in places where cadmium has not been as strongly restricted, product substitution has been slower. Collection and recycling schemes must still ensure proper handling of these last cadmium batteries.

Mercury-containing batteries are strongly restricted in Germany and have been removed from most applications in the EU, following Battery Directive restrictions. However, certain exceptions, such as for special medical devices, still employ mercury when battery size and lifetime performance are critical. The "Act Revising the Law of Waste-Related Product Responsibility for Batteries and Accumulators", or Battery Act (BattG) from 2009 in Germany, restricts button cell batteries to containing up to 2% of their weight in mercury and all other batteries to 0.005% (5mg per kg of mercury). [UBA 2016]

Despite regulations, a study published by the German UBA revealed that a high percentage of non-lead dry-cell batteries POM in Germany contain many more hazardous metals than legally permitted. [Recknagel 2013] This demonstrates that batteries are still globally produced with more hazarous metal content than permitted in many markets. Such batteries very likely enter unregulated battery markets like those found in Ghana and Egypt.

Some batteries and accumulators, such as those containing lithium-ion, can pose a **fire hazard** if improperly handled or transported. Lithium-ion batteries can overheat and burn without easy means of extinguishing the fire. [Linnenkoper, 2014] Though EU laws do not articulately define methods along a battery's life-cycle to mitigate burn risks, precautions must still be taken to ensure handler and transporter safety.

Non-lead dry-cell batteries also contain small amounts of **plastics**, which do not easily disintegrate or may contain hazardous flame-retardent materials. Improper disposal

[1] [CD, 2000] refers to several European List of Waste (ELoW) codes indexed with a star for hazardous covering different waste battery types – "16 06 02* Ni-Cd batteries; 16 06 03* mercury-containing batteries; 16 06 06* separately collected electrolyte from batteries and accumulators" – which are sometimes grouped with lead-acid batteries under "20 01 33* batteries and accumulators included in 16 06 01*, 16 06 02* or 16 06 03* and unsorted batteries and accumulators containing these batteries". Other non-hazardous batteries are categorized as such: "16 06 04 alkaline batteries (except 16 06 03); 16 06 05 other batteries and accumulators."

procedures, like for other unsorted waste, can potentially also pollute the environment when proper care is not taken.

Also of central concern for dry-cell battery disposal is the **material lost** when batteries are only landfilled and their valuable materials not extracted for re-use. These batteries contain many metals, such as cadmium, lithium, nickel, mercury and zinc, as well as plastics that can be reused in new batteries or other applications. Recycling turns waste into a resource, thereby also reducing the amount of primary mining to recover materials for new batteries and other metals applications. Less metals mining results in less instances of the associated mining risks for humans and the environment.

4. Common battery-recycling methods

Batteries may be safely collected in general municipal waste or separately for recycling, depending on the waste system standards available.

For many years, batteries have been generally collected in normal household waste. However, the difficulties in properly disposing of this waste, to prevent leakage and mitigate fire hazards, has encouraged governments to set stricter requirements for waste separation. Consequently, **recycling** through separate waste-collection systems has been prominently seen since the 1990s as a more economically viable method to safely remove batteries from general waste and extract the valuable materials that can be sold for reuse. Various methods are used to process non-lead dry-cell batteries depending on battery composition. The following Table 3 is a sampling of the recycling processes that handle the majority of EoL batteries.

Table 3: Summary of selected recycling methods for common battery types

Battery type	% recyclable material	Materials recycled	Comments on process
Alkaline-zinc and carbon-zinc-air batteries	Up to 100%	Zinc and manganese concentrate Steel Paper and plastic	--
Lithium batteries	>50%	Carbon, as carbon cake sheets Cobalt Lithium carbonate powder (for lithium ingot metal and foil or for lithium metal)	Different from Li-ion battery processing Batteries are crushed and opened Caustic solution to extract metals from electrolytes

Battery type	% recyclable material	Materials recycled	Comments on process
Lithium-ion, nickel-cadmium and nickel metal hydride batteries	Up to 100%	Plastics High-temperature metals: nickel, iron, manganese and chromium Low-temperature metals: zinc, cadmium	Separates plastics from batteries High-temperature metal reclamation (HTMR) process

Source: Oeko-Institut compilation from [Battery Solutions 2016]

Europe and other countries have set up **battery disposal programmes** to log, promote proper disposal awareness, collect, transport and ultimately process EoL batteries. The success of the final step in these recycling systems – the actual material extraction and resale – depends strongly on sufficient collection amounts.

5. EU and German battery collection and recycling

European regulations adopted in the Member States regulate battery collection and processing and require POM batteries to be logged to calculate the efficacy of collection programmes. These regulations and German collection statistics are summarised in this section.

5.1. Current EU regulations for non-lead dry-cell batteries

The EU has set specific objectives for battery recycling-collection rates for all portable (sealed, hand-held batteries), industrial (designed for industrial/ professional use, also for electric vehicles) and automotive batteries (lead batteries for automotive starter, lighting or ingnition power), whether or not they are rechargeable. Under Directive 2006/66/EC, Member States should have reached, by 2012, a 25% battery collection rate by weight of batteries put on the market and, by 2016, a 45% collection rate. [Perchards 2013; 2014]

To calculate collection rates, EU Member States are required to collect statistics to determine the amount of batteries placed on the market (POM) in the country and the amount collected for recycling.

In Europe, producers are required to **register their battery-containing items** in the country wherein they wish to sell before the products are permitted on the market. The EU's Directive 2006/66/EC stipulates how to report collection amounts to calculate collection rates similarly across all reporting institutions. For example, in Germany, the organization Stiftung ear registers all electrical and electronic equipment to facilitate battery collection and pick-up. Using such registries, countries can keep track of battery disposal responsibilities and amounts. **Eucobat** (http://www.eucobat.eu) represents these national registries at a European level to encourage cooperation and exchange. It collects and reports figures on collection rates to achieve European battery collection targets. (See Section 5.3 for current EU rates.)

5.2. EU Directive recycling efficiency specifications and general compliance

EU Directive 2006/66/EC specifies the efficiency of battery recycling processes. For recycling processes that concern the non-lead dry-cell batteries discussed in this report, Article 12 (4) of the Directive 2006/66/EC stipulates recycling minimums of:

(b) 75% by average weight of nickel-cadmium batteries and accumulators;

(c) 50% by average weight of other batteries and accumulators.

The Directive 2004/107/EC from 2004 had already set target values for atmospheric levels of arsenic, cadmium, nickel and polycyclic aromatic hydrocarbons (defined by the marker substance benzo(a)pyrene), with a monitoring requirement for mercury. Current standards stipulate that cadmium should be recycled “to the highest degree technically feasible while avoiding excessive costs.” [Eurobat 2015]

Regulations, however, have not affected the proportions of recyclable materials in non-lead dry-cell batteries. Depending on the battery, 60%-80% of components can currently be recycled. [Battery University 2016] Nonetheless, recyclers report challenges to remain profitable for non-lead battery processing. According to Cadex Electronics, processing non-lead batteries is not generally profitable because of the recycling process complexity (labour-intensive sorting and extraction processes) and the often low amounts of retrievable materials. [Battery University 2016] Consequently, the amount of processing needed to return battery metals to a reusable state is sometimes more costly than current mining standards.

5.3. EU and German battery collection and recycling rates and costs

Commissioned by the European Portable Battery Association (EPBA), the authority representing the portable battery industry, the 2012 **collection goal** (25% battery recycling by POM weight) was reached for all battery categories within most of the 30 EEA member countries[2]. [Perchards 2014] Perchards further reports that EU collection rates per country for all portable and non-lead industrial batteries, as concern this study, reflect a broad range from 14% to 71%. By 2014, all countries had successfully reached the 2012 targets.

The EU calculates a Member State’s battery collection rate as the percentage of batteries collected for recycling out of the total amount of POM batteries. On average in the EU, though POM battery weights have slightly declined since at least 2010, the average number of POM battery units per capita has remained relatively stable at around 19 units per person annually. [Perchards 2014:12] For Germany in 2012, over 1.5 billion units (43 549 t), or approximately **20 batteries per person** annually, were placed on the market. [UBA 2016] Assuming steady per capita POM rates, Germany placed around **1.6 billion battery units or about 48 000 t of batteries on the market in 2015**[3]. One section of a [Perchards 2013] report sought to verify the likelihood of the reported POM volumes. [Perchards 2013:32] The calculation assumed battery purchases per country were proportional to GDP to then compare how parallel a country’s median GDP deviation was with reported POM battery amounts. [Perchards 2013] supposed that GDP offers a relatively consistent guide to per capita annual battery consumption. However, applying GDP for assesing POM volume might only apply in similarly developed countries in northern and western Europe.

Confounding recycling rate calculation, the mixture of POM batteries according to their composition has changed over the years [Eucobat 2013]. Lithium rechargeable batteries, which have a longer lifetime, have increasingly taken over market shares from the more powerful yet shorter-lived alkaline and zinc-carbon primary batteries.

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[2] European Environment Agency: all members *except* Cyprus, Malta and Romania achieved the 2012 goals. (Perchards 2014)

[3] Oeko-Institut calculation using [UBA 2016] and German population figures from [CIA 2016].

In Germany, approximately 15 000 tonnes of EoL dry cell batteries, were separately collected for disposal in 2014. [EUWID 2015] In other terms, Germans properly disposed of approximately eight batteries or 186g per person in 2014 [EUWID 2015], just barely meeting the targeted national collection rate of 45% needed by 2016. [GRS System 2015] This represented over 200 tonnes more batteries nationally than 2013. [EUWID 2015] Representative of other EU non-lead dry-cell battery rates, the UK in 2013 achieved a 32.4% collection rate of POM batteries, which equaled 1702.11 tonnes of disposed non-lead-acid batteries. [NPWD 2014] Many member countries have indicated challenges reaching the 45% collection rate target in 2016. While lead-containing batteries have a positive return on investment, the low to negative value of recycled materials from non-lead batteries reduces producers' incentives for collection initiatives.

Proper battery disposal entails **costs** for public awareness programmes and battery collection, transport and processing. Because much of the overall recycling cost is independent from the individual battery, the cost for recycling programmes decreases as they become more effective. On average, recyclers report that European battery recycling is **not profitable**; public resources are needed to maintain the various programmes. [Battery University 2016]

Each European state has set up its own **awareness programmes**, learning best practice strategies from its neighbours and other members. These programmes are directly linked to collection schemes, informing the public about general battery safety and where and how individuals can dispose of their batteries safely. Various colour-coded systems have proven effective, such as models used by Bebat and GRS in Germany, which are endorsed by Eucobat. These and other battery collection programmes have developed awareness campaigns for schools and e-learning programmes to inform individuals of the need (further discussed in Section 2) for proper EoL battery collection. The costs for such programmes vary greatly depending on the breadth and ambition of the advertising.

Collection campaigns seek to place battery collection recepticles – often cardboard boxes, plastic bags or, increasingly, reusable plastic drums – in easily accessed public locations. The colour-coded recepticles indicate the types of batteries to be collected and encourage individuals to separate damaged batteries from those that are simply discharged. Some collection schemes have installed telemetry systems to inform the battery collection agency when pickup is ideal to maximise returns. [RECHARGE 2015] Depending on the breadth and ambition of the campaign, average collection costs vary per country.

Figure 2: Battery collection boxes near the checkout in a local German supermarket

Source: Oeko Institut

Most recycling schemes in the EU recover all or a majority of dry-cell batteries types mixed together in one container at each collection point. The most effective battery recycling processes require batteries to eventually be sorted by type (see Table 3 above for a description of common recycling processes).

Other campaigns more broadly collect any waste electrical and electronic equipment (WEEE), such as mobile phones and cameras, which may contain batteries. European regulations require that batteries then be separated from the WEEE before further processing and disposal. However, since some reports indicate that separation does not improve the WEEE processing and recycling rates, further investigation would be needed in this area.

From the EoL battery collection points and WEEE separation centres, batteries must be safely transported to disposal centres. **Transport** requires complying with certain hazardous-material safety measures, such as special packaging and labelling, since collection points typically mix all types of non-lead dry-cell batteries including lithium batteries. (The UN Model Regulation for the Transport of Dangerous Goods classifies Lithium-metal and Lithium-ion as Dangerous Goods for Transport.) During transport, non-flammable and electrically-insulating cushion materials, such as sand or other insulating materials, should be used to reduce the risks of fire or overheating. [RECHARGE 2015: 19]

Because of these regulations, only trained drivers with special lorries are legally permitted to carry the (mostly) full disposal containers to the disposal facilities. Depending on transport infrastructure and the proximity of collection points to disposal facilities, transport distances in the United States have been estimated between 50 km and 400 km. [Olivetti et al. 2011: 32] Assuming Europe has overall low average transport distances, each lorry travels on average at least 40 km between various collection points and the battery disposal facilities and slightly more to reach specialised recycling facilities. [based on Olivetti et al. 2011: 32] Overall, **logistics costs** for EoL batteries are assumed to absorb the majority of the total battery disposal cost in Europe. The following Table 4 provides an approximation of German recycling system costs, including costs for collection and logistics, by showing the amount producers and importers to Germany are required to pay per battery category unit or kilogram that they wish to put on the market in 2015.

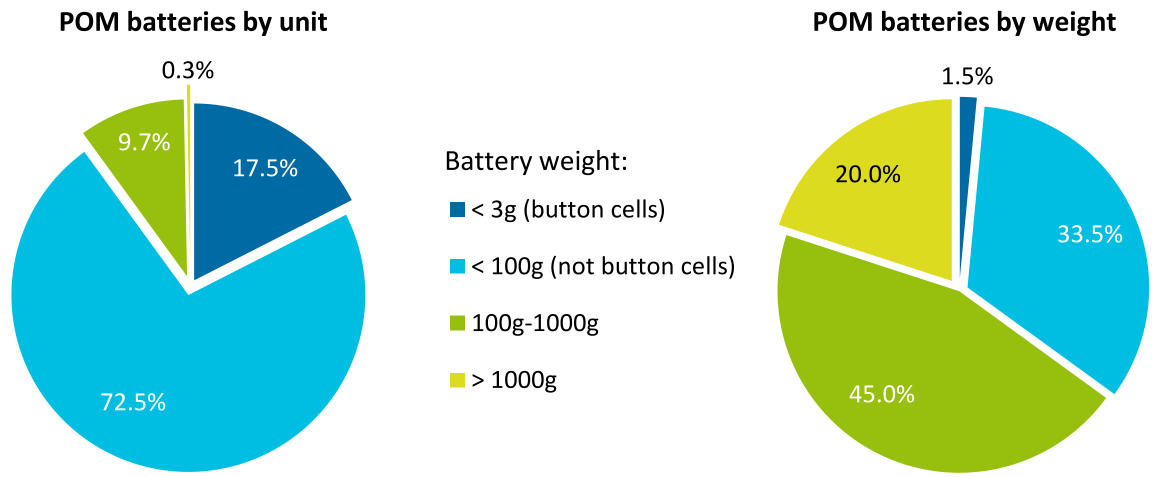
Table 4: Approximate costs (€) for POM batteries in Germany, 2015

Battery Type	**€ / battery**							**€ / kg**	
Battery weight→	**buttons**	**<51g**	**51-150g**	**151-250g**	**251-500g**	**501-750g**	**751-1000g**	**1001-2000g**	**2001-4000g**
Alkaline-manganese	0.004	0.009	0.039	0.080	0.150	0.250	0.350	0.390	0.390
Lithium-ion and lithium-ion polymer (Li-Ion, LIB and LIB-polymer)	0.004	0.010	0.034	0.068	0.128	0.213	0.298	0.340	0.340
Lithium manganese dioxide (MnO2 or Li-M)	0.004	0.015	0.078	0.156	0.203	0.488	0.683	0.780	0.780
Nickel-cadmium (NiCd)	0.004	0.012	0.051	0.102	0.191	0.319	0.446	0.510	0.510
Nickel-metal hydride (NiMH)	0.004	0.005	0.024	0.048	0.090	0.150	0.210	0.240	0.240
Nickel zinc (NiZn)	--	0.009	0.040	0.080	0.150	0.250	0.350	0.390	0.390
Silver oxide, as button cell	0.000	--	--	--	--	--	--	--	--
Zinc air	0.002	0.009	0.045	0.090	0.169	0.281	0.394	0.450	0.450
Zinc-carbon and **zinc-chloride**	--	0.009	0.040	0.080	0.150	0.250	0.350	0.390	0.390

Source: Oeko-Institut compilation of [GRS Entsorgung 2015]

Of all EU battery units placed on the market in 2013, approximately 90% weighed less than 100g, with 17.5% from button cells weighing less than 3g. [Perchards 2014] However, these 90% of battery units account for only 35% of POM batteries by weight, as the blue portions of the graphs in Figure 3 indicate. This discrepancy therefore impacts cost estimations, which are based on battery weights.

Figure 3: Average POM batteries across the EU, longterm data averages



Source: Oeko-Institut compilation from [Perchards 2014]

The data in Table 4 and Figure 3 allow a 2015 estimate of about **1.20€ per capita** spent in Germany to recycle EoL batteries.

6. Current situation for batteries in Ghana and Egypt

For markets where no battery collection and disposal schemes exist, battery-containing devices are, for the most part, also not systematically tracked. As a result, diverse data about sales per battery application must be collected to estimate the **number of batteries placed on these markets** (POM). This count forms the foundation for calculating the various battery disposal costs in battery disposal programmes. Once POM batteries are counted, the amount can be crossed with battery lifetime estimates to approximate the number of devices and hence volume of batteries expected to reach EoL in a given period.

6.1. Preliminary battery disposal cost estimates

Cost estimates for properly disposing of non-lead dry-cell batteries in Egypt and Ghana must include the immediate costs for collection, transport and disposal. In addition, the cost for awareness programmes to encourage individuals and businesses to properly dispose of batteries must be considered. These costs depend on calculating the number of batteries place on the market (POM) for a particular region.

As of 2016, official battery counts do not exist for Ghana and Egypt[4]. However, research indicates that in many developing countries and emerging economies with weak power-supply security and reduced public lighting, yet high mobile phone market penetration, populations tend to more frequently use portable electrical sources – batteries – to ensure telecommunications connectivity, provide lighting and fulfill other energy needs. [Mills 2014; Milz 2013] Battery demand can therefore be assumed to be higher in developing countries than in the EU, where the electrical grid directly fulfils more of the population's electricity needs.

Costs for recycling these batteries in Ghana and Egypt can be estimated using the weight-based GRS battery recycling costs in Germany. (See Table 4 above for exact figures.) As a rough estimation using a top-down approach, this study assumes that, like EU averages, approximately 17.5% of POM battery units in Egypt and Ghana are button cells, 72.5% are not buttons but still weigh under 100g per battery, with the remaining 10% of batteries weighing more than 100g. (See Figure 3.) To roughly estimate the amounts of POM batteries in Ghanaian and Egyptian markets, Oeko-Institut further assumes that the German 2012 per-capita amounts of POM batteries, 20 battery units per person or approximately, must be further **inflated by an average of 10%**. (See Section 5.3 for exact German POM battery figures.) Based on these German statistics along with current population figures,

[4] For this report, no agencies, non-profits or recycling companies active in Ghana and Egypt reported knowledge of battery estimates. See Section 6.2 for a short discussion.

Table 5 below shows the total estimated battery counts for Ghana and Egypt in 2015.

Table 5: Estimated EoL battery amounts for Egypt and Ghana (based on German rates)

(2015 estimations)	Egypt	Ghana
Population [CIA 2015]	88 487 396	26 327 649
Battery consumption, per capita (unit count, from 2012 German rates)	22	22
Estimated total POM batteries (unit count, in millions)	1 900	600
Estimated total POM battery weight (t)	56 500	16 800

Source: Oeko-Institut calculation based on [CIA 2016; EUCOBAT 2013; EUWID 2015; UBA 2016]

Recycling costs for Ghana and Egypt can only be estimated using several assumptions about logistics and labour costs. In Europe, logistics and labour are a major cost burden. Considering the Ghanaian and Egyptian labour cost on the one hand and effort for shipment and treatment abroad on the other, a first guess might be to assume that the total collection and treatment costs to be half of the German costs. For Egypt to recycle approximately 25% of POM batteries, it would cost 10€ to 15€ million; for Ghana's smaller population, this cost would drop to 2.5€ to 4€ million.

Table 6: Estimated 2015 recycling costs (€) for battery disposal in Egypt and Ghana

Costs (2015 estimations)	Egypt	Ghana
Per capita	0.60€	0.60€
Estimated total: for **25% collection rate**	10 - 15€ million	2.5 - 4€ million
for **45% collection rate**	18 - 27€ million	4.5 - 7.5€ million

Source: Oeko-Institut calculation based on [CIA 2016; EUCOBAT 2013; EUWID 2015; GRS Entsorgung 2015; UBA 2016]

Beyond magnifiying the EU's POM battery estimates because of regional usage differences, Egyptian and Ghanaian POM battery counts may also consider **market trends**. The lithium-ion battery's primary market-driver worldwide is its application in portable PCs, including tablets and smartphones, and increasingly in universal power supplies, energy storage systems, medical applications and other telecom uses. [Avicenne 2014: 32]. However, since registered figures of the quantities of POM portable batteries are lacking, the exact distribution of various battery types in Egypt and Ghana can only be estimated to be similar to the battery mix in the EU[5]. Ghanaian and Egyptian battery market trends are therefore not factored into the estimated battery counts.

For more detailed amounts of batteries collected strictly in electronic and mobile phone waste, the Bo2W reports for Ghana and Egypt offer high-estimated figures and projections. (See [Bo2W Ghana 2014] and [Bo2W Egypt 2014]). These reports estimate that the total amount of EoL batteries in Egypt for desktop and laptop computers and mobile phones was

[5] See Eucobat 2013 for more detailed information about the battery mix.

about 36.4 million units in 2015. [Bo2W Egypt 2014] Assuming halved German battery-recycling costs (see Table 4), these e-waste batteries would cost approximately 1.5 € million to recycle. For Ghana, [Bo2W 2012-15] and [Bo2W Ghana 2014] estimate up to approximately 11 million batteries from EoL desktop and laptop computers and EoL mobile phones for 2015. Using halved German disposal costs (see Table 4), this would cost Ghana approximately 0.5€ million to recycle strictly the batteries.

The broad lifetime ranges for different battery types and applications complicates EoL battery amount estimations. For example, WEEE devices and other electronic gadgets that frequently employ lithium-based batteries are often used on average longer in developing countries. [Milz 2013] In contrast, for torches many populations tend to prefer alkaline batteries, which may have shorter overall lifetimes because, among other reasons, environmental conditions can sap alkaline battery energy even as it sits unused on the shelf. [Mills 2014]

As other studies have calculated, projecting the average product lifetime onto the average POM amounts of specific battery-containing goods should provide a rough estimation of EoL batteries in a specified market. However, estimated POM amounts are not available for all battery applications in Egypt and Ghana nor for specific battery types.

6.2. Egyptian and Ghanaian battery disposal experience

Field reports and research indicate an overall low general awareness of the need to collect and properly dispose of dry-cell batteries in most African countries. Batteries are currently discarded in municipal waste.

To promote awareness for battery collection, different United Nations and European Union initiatives are reportedly being initiated. Research and awareness groups agree that recycling programmes for non-lead dry-cell batteries do not yet exist for broad populations in African countries.

7. Proposed dry-cell battery disposal options for the Bo2W project

For any programme to successfully prevent EoL batteries from risking harm to humans and the environment, battery **awareness and collection schemes** must be successfully implemented. These schemes, often initiated in urban areas and managed by government institutions, may choose to follow best-practice recommendations, as summarized and cited in Section 5. As populations become aware of the hazards batteries pose and experience how easily batteries can be separated in well-distributed collection recepticles, the programmes can be expanded to less densely populated areas and ultimately run by private industry or producer responsibility schemes.

Battery separation from standard waste is only the first step. **Transport systems** must ensure that EoL batteries can reach their disposal destination safely. Governments would need to regulate such hazardous waste transport, including for non-lead dry-cell batteries, to encourage safe practices. Especially for disposal options that require waste export from the home country, certifications for hazardous transport licensing should be required and officially verified.

Stockpiling areas should also be verified that they are leak-proof and that the collected batteries are properly dispersed. Best practice should be followed, such as using insulating flame-retardant packaging or other materials to reduce the risk of fire. A primary and significant concern with battery stockpiling is that lithium, a component in many of this study's batteries, can be explosive. This poses dangers to waste workers and risks damaging waste disposal facilities. Authorities should also remember that lithium fires can be difficult to extinguish. To ensure that protective standards are met, authorities would need to be trained and organised.

As will be discussed in the following two subsections, this study found two options for non-lead dry-cell battery disposal in Ghana and Egypt:

A. Battery disposal in specially-protected sections of national hazardous waste disposal sites.

B. Separate battery collection and recycling, including a transitional period of export to advanced recycling facilties until a national (or transnational) system can be established.

To choose the best solution, all of which require **public investment**, the feasibility and appropriateness of each disposal option should be evaluated by comparing EoL battery counts to the minimum viable input volume necessary for running each battery disposal option. Initial programme launch costs and demand on public coffers can then be calculated and compared.

To help boost the success of the selected disposal option, WEEE components should be considered. Earlier stages in the Bo2W project observed that the waste sector increasingly targets WEEE components. [Bo2W 2012-15] Consequently, batteries are frequently separated from WEEE, for example button cells in printed circuit boards or Li-Ion batteries from mobile phones. However, these batteries are often only stored without proper disposal options. The stockpiles from this business could provide a starting point to establish initial battery flows for correct hazardous waste disposal or recycling.

The following subsections will explore the two proposed disposal possibilities.

7.1. Option A: National hazardous waste disposal scheme

For final disposal of EoL batteries, though no longer widely practiced, EoL batteries, like other hazardous wastes, are packed into drums that are securely stored or buried. For this, batteries are first separately collected at centres in interim storage until full drums are ready for storage or burial. To follow this waste disposal scheme, only some technical know-how, for example in how waste storage drums are constructed, is necessary to inform procurement decisions; most workers can be trained locally in proper waste collection, packaging, sealing and storage practices. While equipment can be very expensive and storage space is needed for final disposal, labour costs for highly trained workers are reduced.

A significant drawback for this Option A is the loss of valuable and essential materials into waste that is not reused. Authorities should be aware that batteries contain valuable resources that, with proper recycling techniques, can be extracted and sold into production chains. However, despite the loss of materials to waste, hazardous waste disposal schemes successfully remove batteries from the environment and general municipal waste, thereby reducing risks to humans and the environment.

Another disadvantage for final disposal is the volume of hazardous waste that must be processed even though only a small percentage of the waste content is actually hazardous. For example, mercury-containing batteries on regulated markets generally contain at most 2% mercury of the battery's weight, along with some other hazardous metals. If the hazardous content in the battery is extracted, the overall volume of hazardous waste would be remarkably reduced, since the non-hazardous waste within batteries (e.g. certain metals) could be disposed of as part of non-hazardous waste and recycling streams.

7.2. Option B: Hazardous waste recycling

Recycling EoL batteries is an option that recuperates the valuable and essential materials contained in non-lead dry-cell batteries while mitigating the risks inherent in battery disposal. It allows critical materials and raw minerals to not only be removed from hazardous waste streams but to also be reused in new products. This can minimise the amounts of generated waste needing proper disposal as well as reduce the demand for virgin materials.

Setting up recycling programmes requires safe transport systems and appropriate know-how to manage recycling facilities and set up recycling systems. Since the annual volume of EoL batteries is relatively low, at least during the first years of implementation, governments may have time to investigate recycling options and attract the necessary know-how to inaugurate recycling facilities. For this, public bids for battery transporters and recyclers could be used to attract business.

If recycling initiatives in the home country are deemed not a viable option, recycling facilities in Europe, Asia and the Americas might offer the required services. Transport systems that comply with international standards on hazardous waste transport would need to be investigated and bids would need to be collected for these international services.

7.3. Hybrid approach combining Options A and B

To successfully implement battery separation schemes, a hybrid approach combining Option A and Option B, might return more optimal battery disposal results, as summarised in Figure 4. From Option A, the hybrid approach adopts storage activities. In parallel, the recycling initiatives from Option B can commence, where possible and necessary to cover larger geographical regions than just within one country.

For any waste collection scheme to safely dispose of EoL batteries, **awareness programmes** must be initiated and widely publicized in parallel with collecting batteries (see step A in Figure 4). Because of the high population density in urban areas, such awareness programmes are often most effective in cities and can gradually be spread to more rural areas as the concepts enter common knowledge. While awareness and collection schemes are taking hold, **batteries extracted from WEEE** (A1), which in many regions may already be separately collected, can provide initial collection volumes to later support reaching the minimum viable inputs into disposal schemes.

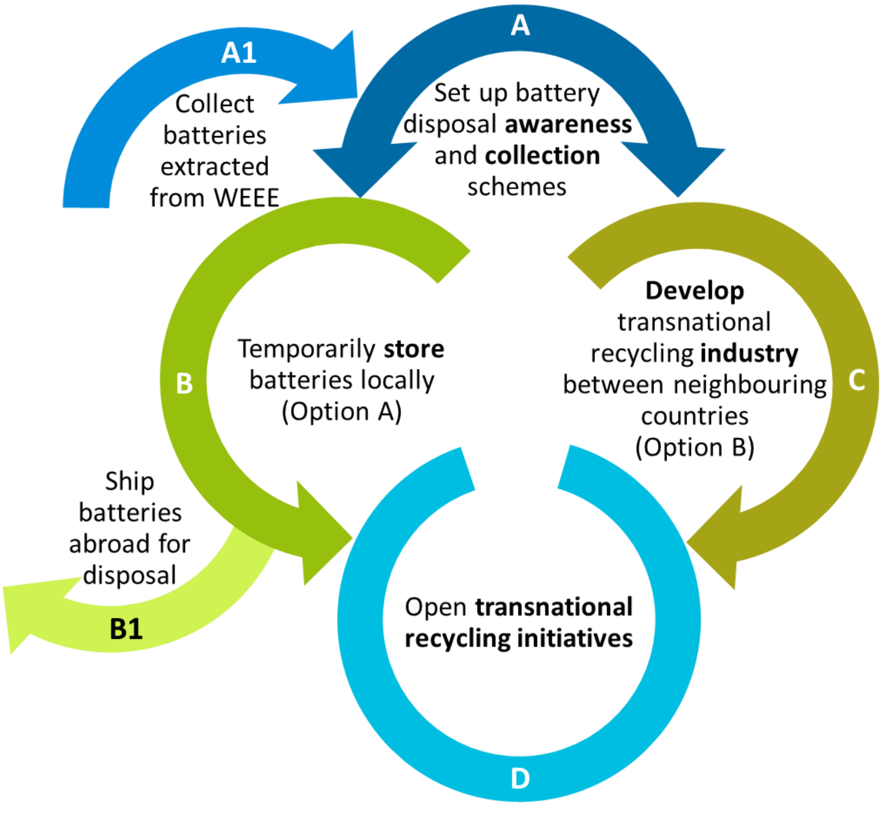
Like for Option A proposed in Section 7.1, collected batteries, mostly from urban areas, can be safely **transported and stockpiled** at specialised battery storage facilities, when possible conveniently located near waste management facilities (step B in Figure 4). If these storage centres become overfilled before permanent disposal options are developed, batteries can be exported (B1) to recycling or disposal facilities abroad following international standards for EoL battery transport.

While awareness of battery collection campaigns becomes more widespread and batteries are stockpiled temporarily, investment and development activities can work toward setting up **regional or transnational recycling locations** (step C in Figure 4). Neighbouring countries could unite to invest in a central battery-recycling facility that serves the region. Alternatively, one country could initiate recycling schemes and take on contracts with its neighbours for responsible recycling. This step, similar to Option B proposed in Section 7.2, aims to set up recycling centres using pooled transnational resources from neighbouring countries and leaves local populations with more economic control over managing their waste.

As soon as local recycling-industry initiatives become operational, batteries can be **recycled** (step D in Figure 4) *without* needing local storage or processing abroad (steps B and B1). Strengthening the transnational cooperation, countries could share their best-practice experiences and ideas for setting up and maintaining other aspects of this hybrid approach.

Public funding of less than 1€ per inhabitant could be used to attract private industry by opening bids for battery collectors, transporters and the separation and recycling processes. Once the system matures, public funding might be transferred to producer resposibility schemes funded by fees on products placed on the market.

Figure 4: Hybrid approach (Options A+B) for battery disposal



Source: Oeko-Institut

This hybrid approach uses awareness and collection campaigns to provide the foundation for supporting the development of parallel systems – storage and transnational recycling industry – to inaugurate transnational battery-recycling initiatives.

8. Conclusion

Battery recycling seeks to protect humans and the environment by reducing the human and environmental risks associated with the dangerous metals in EoL non-lead dry-cell batteries, while at the same time allowing batteries' valuable metals to be reused. Research into the disposal options for non-lead dry-cell batteries has indicated two viable options for disposal schemes in Egypt and Ghana: disposal in separate sections at waste centres (Option A) or recycling in local or foreign facilities (Option B). Both options, drawing on European recycling schemes that are regulated by law, would successfully address the main environmental and human health concern to prevent EoL batteries from releasing their contents in an uncontrolled manner into the surrounding environment or from starting fires when they overheat. Since the operational efficiency of such schemes has not been piloted in Ghana or Egypt, no certain predictions can be made about financial success. Funding schemes for battery recycling were not the central focus of this report.

This study estimates that, at least during the first years of transitional phase, the volume of EoL batteries would be low. Combining the two summarised options, this study proposes a **hybrid approach** to managing EoL batteries, which would allow immediate separation of hazardous materials from general waste. The scheme would start with a transitional phase of bulk battery storage, exporting batteries for recycling when needed, with the aim to establish national or transnational recycling options.

9. Literature

Avicenne 2014	Avicenne Energy (Pillot, C). (Sep 2014). Battery market development for consumer electronics, automotive, and industrial: materials requirements and trends. Available from http://www.rechargebatteries.org/wp-content/uploads/2015/01/Avicenne-market-review-Nive-2014.pdf. Presented 24-26 Sep. 2014.
Avicenne 2015	Avicenne Energy (Pillot, C). (May 2015). Battery market development for consumer electronics, automotive, and industrial: materials requirements and trends. Available from http://www.avicenne.com/pdf/BMDCEAIMR_C_Pillot_Presentation_5th_Israeli_Power_Sources_Herzelia_May2015.pdf. Presented at 5th Israeli Power Sources Conference 2015. 21 May 2015.
Battery Solutions 2016	Battery Solutions. (2016). Recycling process: end sites recycling processes. [website] Available from http://www.batteryrecycling.com/Battery+Recycling+Process. Accessed in Jan 2016.
Battery University 2016	Battery University, Cadex Electronics. (2016). BU-705a: battery recycling as a business. [website] Available from http://batteryuniversity.com/learn/article/battery_recycling_as_a_business. Accessed in Jan 2016.
Bo2W 2012-15	Oeko-Institut. (2012-2015). Global circular economy of strategic metals – the Best-of-Two-Worlds Approach (Bo2W).
Bo2W Egypt 2014	Oeko-Institut. (Jul 2014). Global circular economy of strategic metals – the Best-of-Two-Worlds Approach (Bo2W): Work package 2.2. Status analysis Egypt; Work package 2.4 Generation of WEEE and ELV; Work package 3.2 Status analysis of Egypt regarding collection, sorting and pre-treatment.
Bo2W Ghana 2014	Oeko-Institut. (Apr 2014). Global circular economy of strategic metals – the Best-of-Two-Worlds Approach (Bo2W): Work package 2.2. Status analysis Ghana; Work package 2.4 Generation of WEEE and ELV; Work package 3.2 Status analysis regarding collection, sorting and pre-treatment in Ghana.
Buchmann 2015	Buchmann, I. (2015). Battery university – BU-106: advantages of primary batteries. http://batteryuniversity.com/learn/article/primary_batteries. Accessed in Dec 2015.
Crown 2015	Crown & Department for Environment, Food and Rural Affairs. (Jan 2015). Digest of waste and resource statistics – 2015 edition. Available from http://www.gov.uk/government/collections/waste-and-recycling-statistics.
EC 2011	European Commission. (Dec 2011). Comparative life-cycle assessment of nickel-cadmium (NiCd) batteries used in cordless power tools (CPTs) vs. their alternatives nickel-metal hydride (NiMH) and lithium-ion (Li-ion) batteries: Final Report. Available from http://ec.europa.eu/environment/waste/batteries/pdf/report_12.pdf.
EEA 2012	European Environment Agency. (2012). Heavy metal emissions. Available from http://www.eea.europa.eu/data-and-maps/indicators/eea32-heavy-metal-hm-emissions-1/assessment-2. Accessed in Jan 2016.
Energizer 2012	Energizer. (2012). Alkaline manganese dioxide: handbook and application manual. Available from http://data.energizer.com/PDFs/alkaline_appman.pdf.

EPBA 2015	EPBA. (2015). The EPBA presents the 2014 update to its portable battery collection report. Available from http://www.epbaeurope.net/documents/Pressreleasecollectionreport.pdf.
ERP 2012	European Recycling Platform. (Mar 2012). How are batteries recycled? Available from http://www.erp-batteries.co.uk/wp-content/uploads/2012/03/Batteries-Recycling-Facts-WEB.pdf.
EUCOBAT 2013	Eucobat. (Oct 2013). Position paper: collection rate according to the battery directive. Available from http://www.eucobat.eu/system/files/PP%20Collection%20Rate%20v1.3.pdf.
EUROBAT 2015	EUROBAT; & Gasparin, N. (2015) Automotive battery market outlook update 2015: a report of the EUROBAT automotive battery committee. Available from http://www.eurobat.org/sites/default/files/automotive_battery_market_outlook_-_update_2015_0.pdf.
EUWID 2015	EUWID Recycling und Entsorgung. (May 2015). GRS Batterien erreicht erneut Sammelquote von 45 Prozent. Available from http://www.euwid-recycling.de/news/wirtschaft/einzelansicht/Artikel/grs-batterien-erreicht-erneut-sammelquote-von-45-prozent.html
GRS 2007	Stiftung Gemeinsames Rücknahme System. (2007). The world of batteries: function, systems, disposal. Available from http://www.grs-batterien.com/fileadmin/user_upload/Download/Wissenswertes/Infomaterial_2010/GRS_WDB_eng.pdf. Accessed Dec 2015.
GRS Entsorgung 2015	Stiftung Gemeinsames Rücknahme System. (2015). Entsorgungskostenbeiträge für Gerätebatterien bis 1000g. Available from http://www.grs-batterien.de/fileadmin/user_upload/Download/Vertr%C3%A4ge_und_Dokumente/GRS_Entsorgungskostenbeitr%C3%A4ge_Deutsch.pdf. Accessed Dec 2015.
GRS System 2015	Stiftung Gemeinsames Rücknahme System: Stiftung GRS Batterien. (Feb 2015). Annual Review 2014. Available from http://www.grs-batterien.com/fileadmin/user_upload/Download/Wissenswertes/GRS_Erfolgskontrolle2014_Web_PDF_Engl.pdf.
Linnenkoper 2014	Linnenkoper, K. (Nov 2014). Electric vehicle dangers and other dilemmas: battery safety: how to douse. Available from http://www.drossengineering.com/web/IMG/pdf/1409_-_Batteries-3.pdf.
Mills et al. 2014	Mills, E.; Tracy J.L.; Alstone P.; Jacobson, A.; and Avato, P. (Aug 2014). Low-cost LED flashlights and market spoiling in Kenya's off-grid lighting market. Available from http://evanmills.lbl.gov/pubs/pdf/mills-etal-led-market-spoiling.pdf. DOI: 10.1007/s12053-014-9294-2.
Milz 2013	Milz, E.; (2013). Bedeutung der Einwegbatterien im afrikanischen Haushalt. Available from http://www.aktuell.solarenergie-fuer-afrika.de/?download=Batteriereferat%20Arwed%20Milz%202013.pdf
Mudgal et al 2010	Mudgal, S. et al. (Oct 2010). Review of the community strategy concerning mercury: reference 07.0307/2009/549558/ETU/G1. Available from http://ec.europa.eu/environment/chemicals/mercury/pdf/review_mercury_strategy2010.pdf.

NPWD 2014	National Packaging Waste Database. (Jun 2014). Summary of portable batteries data for the 2013 compliance period: as at 26 June 2014. Available from https://npwd.environment-agency.gov.uk/FileDownload.ashx?FileId=f070e4e3-2af5-4824-a7d0-65f40ce25ca0.
Olivetti et al. 2011	Olivetti, E.; Gregory, J; Kirchain, R. (Feb 2011). Life cycle impacts of alkaline batteries with a focus on end-of-life.
Perchards 2013	Perchards; SagisEPR.com & EPBA. (Aug 2013).The collection of waste portable batteries in Europe in view of the achievability of the collection targets set by Batteries Directive 2006/66/EC. Available from http://www.epbaeurope.net/documents/Perchards_Sagis-EPBA_collection_target_report_-_Final.pdf.
Perchards 2014	Perchards; SagisEPR.com & EPBA. (Dec 2014).The collection of waste portable batteries in Europe in view of the achievability of the collection targets set by Batteries Directive 2006/66/EC. Available from http://www.epbaeurope.net/documents/Reportontheportablebatterycollectionrates-UpdateDec-14-fullversion_LUadded.pdf.
PowerStream 2015	PowerStream. (Nov 2015). PowerStream battery chemistry FAQ. Available from http://www.powerstream.com/BatteryFAQ.html#lec.
RECHARGE 2013	RECHARGE. (Feb 2013). Advanced rechargeable batteries: on the road to sustainability, supporting a resource efficient circular economy and low carbon society. Available from http://www.rechargebatteries.org/wp-content/uploads/2013/03/P2-Recharge-Sustainibility-Report-complete-version-25Feb13.pdf.
RECHARGE 2015	RECHARGE. (Mar 2015). Sustainability Report: The contribution of advanced rechargeable batteries to the EU agenda and initiatives on climate & energy, raw materials & resource efficiency. Available from http://www.rechargebatteries.org/wp-content/uploads/2015/03/Recharge-Sustainability-Report-f.pdf.
Recknagel 2013	Recknagel, S. & Radant, H. (Sep 2013). Überprüfung der Quecksilber-, Cadmium- und Blei-Gehalte in Batterien: Analyse von Proben handelsüblicher Batterien und in Geräten verkaufter Batterien. Erstellung eines Probenahmeplans, Probenbeschaffung und Analytik. Available from https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4438.pdf. Accessed in Jan 2016.
UBA 2012	Umwelt Bundesamt. (2012). Batterien und Akkus: ihre Fragen – unsere Antworten zu Batterien, Akkus und Umwelt. Available from https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4414.pdf.
UBA 2016	Umwelt Bundesamt. (2016). Batteries. [Website] Available from https://www.umweltbundesamt.de/en/topics/waste-resources/product-stewardship-waste-management/batteries. Accessed Jan 2016.
Van Peperzeel 2010	Van Peperzeel & van Peperzeel, J.H. (2010). Used lithium batteries collection, Brussels 31-8 and 1-9 2010. Available from http://www.ebra-recycling.org/sites/default/files/ITEM_10_J_VPPZL_Li_Coll___Recycling_DAY_2.pdf. Presented 31 Aug and 1 Sep 2010.