Management of End-of-life Li-ion Batteries through E-waste Compensation in Nigeria

Feasibility study on options for developing environmentally sound recycling solutions in Nigeria

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Abstract

The following study addresses the possibilities for responsible management of end-of-life lithium-ion batteries from domestic consumption in Nigeria. As there are currently no recycling and final treatment capacities for such batteries installed in Nigeria, it explores options for setting-up such capacities, including technical aspects and investments needs. The study takes into account the wider end-of-life battery recycling landscape and has an additional focus on feasible management options under an e-waste compensation scheme. E-waste compensation is a concept where manufacturers and/or users of IT contribute to sustainable recycling of end-of-life devices. The study was carried-out under the project E-waste Compensation as an international financing mechanism in Nigeria (ECoN) with the project partner Closing the Loop organizing environmentally friendly and suitable collection, transport and final management together with the partners Verde Impacto Nigeria, Hinckley Recycling Ltd., in Nigeria. SRADev Nigeria and Oeko-Institut e.V. guide the project from a scientific and local policy perspective.

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It is not possible to name all the people who contributed to this study. However, we would like to mention some of them by name and explicitly thank them for their great cooperation in this pilot project:

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The ECoN project team

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1 Background & purpose of the study

This report was developed within the project *E-waste Compensation as an international financing mechanism in Nigeria (ECoN)*, which is funded under the PREVENT Waste Alliance. The ECoN project aims at advancing the concept of ‘e-waste compensation’, where international brands and users of electronic equipment can contribute to a sound management of equivalent e-waste volumes in developing countries by providing finances to an organization that organizes collection and environmentally sound management of e-waste on behalf of the brands and users. The project is conducted by Öko-Institut e.V. Closing the Loop, Hinckley Recycling, SRADev Nigeria and Verde Impacto Nigeria.

This report specifically addresses the possibilities for responsible management of end-of-life lithium-ion (Li-ion) batteries from domestic consumption in Nigeria. While this takes into account the wider e-waste and recycling landscape in the country, the main focus is on feasible management options under an e-waste compensation scheme in Nigeria. The primary focus is on batteries from mobile phones, which are mostly individual pouch cells with high cobalt content. Other battery types are not specifically in scope, but it cannot be excluded that collection efforts also yield other Li-ion battery types or even other battery chemistries. Thus, the handling of such batteries is shortly elaborated on in section 4.5.

The study elaborates on the concept and aims of e-waste compensation (chapter 2), the health, safety and environmental aspects relevant for Li-ion battery recycling (chapter 3) and responsible management options for Li-ion batteries under the given Nigerian context (chapter 4). In chapter 5, the economic aspects of Li-ion batteries are described. Based on this analysis the study suggests next steps for advancing Li-ion battery management in the context of e-waste compensation (chapter 6).

2 About e-waste compensation

The concept of e-waste compensation was developed by Closing the Loop (CTL) and builds upon the finding that many tech purchasers aim to procure electronics in a way that better aligns with their (personal) values. However, the purchased devices are often linked to environmental and health problems, due to unsound e-waste management in many low- and middle-income countries. Through a voluntary financial contribution, these purchasers can assign a third party to make sure a defined e-waste volume is collected in one or more target countries and consequently managed in an environmentally sound manner. The approach is used to compensate a purchase, it makes a new device 'waste-neutral'. Closing the Loop has set up and is operating such an e-waste compensation scheme for public and corporate customers (predominantly located in Europe). To do so, CTL cooperates with the local informal sector, as well as with e-waste recycling and management companies in various African countries who manage collection networks to make sure the requested amounts of e-waste is prevented from ending up in landfills or harmful recycling and channelled to their facilities for sound treatment. So far, these schemes were limited to mobile phones, tablets & notebooks and based on a 1-to-1 principle, where each customer finances the collection and management of a defined number of devices (this number commonly correlates with the number of devices brought onto a defined market in Europe). In that context it is important to note that e-waste compensation does not replace legal obligations for participating in an Extended Producer Responsibility (EPR) scheme in the country where the equipment is brought onto the market. E-waste compensation is a voluntary additional measure which delivers on the large and growing demand for green electronics procurement. It results in the support of collection and e-waste recycling systems in countries with widely unregulated e-waste landscapes. The logic for this is that many IT devices do not reach end-of-life in the market where they were originally introduced.

The concept of e-waste compensation was also taken up by the eco-labelling scheme TCO Certified: Companies applying for a TCO-edge certification for their mobile phones, tablets or notebooks must prove that 'for every manufactured unit of the product, the brand ensures take back of an equal amount of e-waste that already exists on the market in a country that lacks proper e-waste recycling capacity.' (TCO Development 2019; 2020a; 2020b). This shall be achieved by the following mechanism:

- 'The brand owner purchases offsetting from an approved collector, compensating for the potential e-waste of the certified product.
- The approved collector uses the fee to pay for the collection of the corresponding e-waste amount of end-of-life products that are no longer relevant for normal use. The collection takes place in regions where there is a lack of functional take-back systems.
- If responsible recycling is not possible locally, the approved collector must transport the e-waste to recycling facilities fulfilling high environmental standards.
- The offsetting for the certified product is continuously verified by an approved independent verifier.' (TCO Development 2019; 2020a; 2020b).

While this model is comparably new in the e-waste management field, similar approaches also exist for plastic and packaging waste (plasticbank; Plastic Fischer).

On the one side, e-waste compensation is a way to align (the purchase of new) electronic devices with organisations' values and ambitions. These can be commercial ambitions (such as employee engagement or company branding) as well as responsibility/moral ones (being a good corporate citizen). By providing organisations with a commercially interesting solution to make their IT consumption more sustainable, it allows these organisations to get started on the rather challenging concepts of sustainable procurement and sustainable operations.

On the other side, the concept aims at various objectives within the countries where e-waste is collected:

- To avoid that unsound handling, recycling and disposal of such products leads to pollution and adverse effects on human health and the environment;
- To open business opportunities for local waste management and recycling operators that comply with national regulations and that apply environmentally sound processes;
- To support the increase of local awareness, value-addition and investments in environmentally sound reuse and recycling.

To contribute to these objectives, the following additional principles implicitly apply:

1 | Local sourcing: E-waste compensation is aimed to manage waste from local consumption in the countries the collection takes place. It shall by no means stimulate any imports of e-waste to such countries and operators of compensation schemes shall take convincing measures to ensure that e-waste collected and processed under such arrangements comes from local consumption.
2 | Additionality: E-waste managed through compensation mechanisms should also come from a waste stream that would – without the scheme – most likely be managed in an unsound and polluting manner (e.g. open dumping, burning, crude recycling). It must therefore be avoided that compensation addresses waste volumes for which another player (e.g. the previous owner of the equipment) has already commissioned (and paid for) sound end-of-life management.

A further aspect that may need further discussion and public consultation is the question of what technical level the management processes shall comply with: While the first objective above (avoiding pollution) calls for a high ambition approach, the third objective might call for compromises in fields where highest recycling standards may – at least in the short term – only be realised through export of full devices to companies applying highest standards.

While this study cannot give an exhaustive answer to this question, the following chapters explore feasible and meaningful ways to manage end-of-life Li-ion batteries under e-waste compensation schemes in Nigeria.

3 Health, safety & environmental aspects

Since its introduction in 1991, the lithium ion battery (LIB) has experienced rapid market growth. However, the sound end-of-life treatment of the batteries has not been fully developed yet and is still far away from being perfect, even in highly developed countries. Especially the safety can be a critical issue when it comes to transport, storage, and recycling of end-of-life (EoL) LIBs. In particular, improper transport, storage or handling may result in internal and external short circuits due to thermal effects or mechanical damage. For an LIB, a short circuit can lead to fire or explosion and have serious consequences for people and the environment. Especially in general waste treatment plants in Europe, it is well documented that such fires resulting from incorrectly disposed LIBs have increased significantly in recent years. In the UK alone, about 250 fires in waste treatment plants have been related to wrongly disposed LIBs from April 2019 to March 2020 (Carrington 2020). Storing LIBs for a long period of time without close monitoring and safety measures or simply landfilling them is not an option as the risk of fire is too high.

In addition, there are many hazardous substances in the LIB that can also make treatment or recycling a challenge. The electrolyte, consisting of different carbonate-based solvents, as well as the standard conducting salt, lithium hexafluorophosphate (LiPF6) are part of nearly all LIBs. During the lifetime of a LIB, the conductive salt and its solvents partially decompose due to the harsh environment inside of a battery and some hazardous organic chemicals are produced, that have characteristics similar to warfare agents (Menzel et al. 2017). The conducting salt in particular can cause major problems, as it easily decomposes into hydrofluoric acid (HF), a very toxic and corrosive substance, when it comes into contact with moisture (e.g. from the air).

In addition, the dust produced during the manufacture and recycling of LIBs is carcinogenic and often toxic, which is particularly problematic when it is suspended in the air and inhaled. This is especially the case when the materials are dry, i.e. when the electrolyte has evaporated. In addition, some LIBs also contain cobalt and nickel, both of which are toxic for humans and very harmful to the environment when released into the ground, for example, dissolved in water (Sojka et al. 2020). This is another reason why the uncontrolled disposal of LIBs must be avoided under all circumstances.

4 Management options

4.1 Collection

Collection of e-waste and EoL batteries in Nigeria is mainly organised through collection networks that operate on an economic incentive level. While waste types containing valuable materials (e.g. copper, aluminium) are collected to be sold to scrap dealers (possibly after dismantling and liberation of the target materials), waste types with no local market value are typically neglected by such networks and are managed together with the residual municipal solid waste stream (mostly open dumping and burning, or disposal).

In this situation, the most effective means of collection is to set an incentive for collectors who bring LIBs of a defined type and quality. Hinckley and CTL work with Verde Impacto Nigeria, a registered collector with 25 agents and around 60 associated collectors in various parts of the country. These agents and collectors use such monetary incentives for delivered EoL LIBs from mobile phones. According to International Telecommunication Union, there were more than 172 million mobile phones in use in Nigeria in 2018 (ITU 2021). Assuming an average battery lifetime of 3 years and an average battery weight of 40 g, the total generation of end-of-life LIBs from mobile phones can be estimated at around 6880 t per year in Nigeria. Therefore, the abundance of end-of-life LIBs should not be a limiting factor for battery collection systems, and it can be assumed that the collection volumes will strongly correlate with the applied incentive level and the number of involved agents and collectors.

It should be noted that the project's collection efforts experienced competition around EoL mobile phone batteries, particularly in Lagos. Although no details are known on other collectors and the whereabouts of batteries, it is assumed that activities are linked to crude recycling practices (see section 4.4.2).

Figure 1: Typical EoL mobile phone batteries collected in the pilot

Source: Closing the Loop

As handling of EoL LIBs entails various health and safety risks (see section 3), training was given to the collectors to raise awareness on the risks, and to give guidance on how to mitigate fire and explosion risks, as well as emissions from the batteries. Amongst others, the training encompassed the following aspects:

- Never accumulate and store larger volumes of batteries at one place. Instead use small buckets or sacks and do place them with some distance from each other.
- Cover open contacts of batteries with isolation tape.

- Never store any old lithium-ion batteries in your home where you or other people are staying and living.
- Store batteries well removed from flammable materials such as plastic, wood and paper.
- Handle all batteries with care and avoid exposure to heat, direct sunlight, moisture and mechanical stress.
- All batteries that are damaged must be placed in plastic buckets or drums filled with dry sand (some cm of sand, 1 layer of batteries, some cm of sand, one layer of batteries…)
- Old Li-ion batteries might release some toxic gases. Thus, make sure the storage area is well ventilated.
- Old Li-ion batteries, when damaged, may also release toxic and corrosive liquids. Therefore, wear nitrile disposable gloves, long sleeve work cloths, closed shoes and safety goggles when handling damaged batteries.
- Place a water bath and buckets with sand close to where you handle and storage batteries.
- Always keep emergency pathways free.
- In the case one battery heats-up (smoke), throw it into the water bucket if this is still possible. Otherwise, use sand or class B fire extinguisher (dry powder or dry chemical fire extinguisher) for firefighting.
- In case of larger fires, evacuate the place and warn others. Be aware of explosions when the batteries reach a certain critical temperature.

It is noteworthy that EoL LIBs are collected and accumulated also through other means and mechanisms in Nigeria. These volumes typically come through B2B arrangements between companies and local recyclers (including Hinckley) to manage defined streams of battery containing equipment and EoL batteries. Most such arrangements exist with energy-access providers (e.g. providers of solar home systems) who collect equipment and batteries in conjunction with warranty and servicing activities, and who are interested in environmentally sound management of their waste.

While such deliveries of EoL batteries from corporate customers are important elements for reforming the national e-waste management landscape in Nigeria, the volumes are considered not to be eligible under e-waste compensation schemes, as their environmentally sound management has already been commissioned by other parties (see section 2).

4.2 Handling & storage

Handling and storage of large volumes of EoL LIBs is associated with significant risks, particularly fire risks (see section 3). Therefore, handling and storing must follow stringent procedures:

- Batteries must be handled with care. Physical stress and exposure to heat and moisture must be avoided. Battery handling shall also minimize the risks of unintended short circuiting (e.g. by avoiding the use of metal containers, by isolating the battery poles with tape).

- Collected batteries must be sorted upon arrival at the facility. This step aims at separating alien materials and all other battery chemistries (e.g. nickel metal hydride batteries (NiMH), nickel cadmium batteries (Ni-Cd) and lead-acid batteries (LABs)) from LIBs. These other battery types must be handled as sketched in section 4.5.
- All handling and sorting processes shall be conducted close to one or more large water containers. In case of overheating of an individual battery, it should be thrown into the water, which effectively cools and slows down the chemical reaction in the battery. Note: The use of water is only recommended when the volume of water clearly exceeds the volumes of batteries (e.g. by a factor of 1000). For all other cases, a class B fire extinguisher is preferable (see below).
- LIBs must be stored in small lots and embedded in dry sand (or similar packaging material such as vermiculite). Individual lots (e.g. buckets with LIBs embedded in sand) should be placed in some distance from each other to avoid chain reactions in case of overheating and fire.
- LIBs shall be stored in a place well sheltered from rainfall, stormwater and direct sunlight. The storage space shall have a sealed ground and be well ventilated. No flammable materials (wood, plastic) shall be stored in the vicinity of the LIBs.
- The LIB storage area should not be used for any other purposes.
- LIB battery handling and storage areas should have clearly marked, and well accessible emergency exits and must be equipped with easily accessible fire extinguishers of class B (dry powder or dry chemical fire extinguisher).
- All persons involved in handling and storage of LIBs must be properly trained and made aware of risks and emergency response strategies.

4.3 Reuse & repurposing

In the absence of any end-of-life management solution for LIBs in Nigeria, as well as the challenges and costs associated with either export and local pre-processing (see section 4.4), testing and reuse/repurposing[1] of functional cells or battery packs is a management option that can help to reduce the accumulation for EoL batteries for recycling and/or disposal and to generate an income stream from the sale of second-hand batteries and products. In light of the generally accepted waste hierarchy, reuse/repurposing shall be prioritized over recycling and disposal activities, so that related strategies are in-line with circular economy principles. Hinckley recycling is exploring the feasibility of battery reuse and repurposing for the reasons given above. Nevertheless, reuse and repurposing activities have limitations for e-waste compensation schemes:

- Reuse and repurposing are already established business activities in many small local repair shops and mobile phone LIBs are commonly used to produce low-cost power banks for the local market. These activities also result in a situation where LIBs with reuse potential are not given to collection networks. Experiences in battery collection have shown that almost all collected batteries are unsuitable for reuse and repurposing (also see Figure 1).

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[1] The terms are used in-line with the definitions of the proposal for a new Battery Regulation as published by the European Commission in December 2020 (European Commission (2020), where 'reuse' 'means the complete or partial direct re-use of the battery for the original purpose the battery was designed for; [and] 'repurposing' means any operation that results in parts or the complete battery being used for a different purpose or application than the one that the battery was originally designed for.'

- High quality reuse and repurposing activities require deliveries of similar or even uniform battery types. But the collection of batteries from mobile phones through collection networks (see section 4.1) yields a broad mix of different battery types that are mostly quite old and with no known history about usage and potential damages. Reuse and repurposing of such batteries has limited potential and would generate product quality and safety issues.

Subsequently, reuse and repurposing of locally collected LIBs from mobile phones is currently not a promising management option for e-waste compensation.

4.4 Further treatment options

Recycling of end-of-life (EoL) lithium-ion batteries (LIBs) is rapidly developing with around 30 companies (as of 2020) running large scale or pilot industrial plants to recover embedded metals, particularly cobalt, nickel and copper, but also other materials including manganese, lithium and graphite (Sojka et al. 2020).

In general, the development of recycling technologies is still advancing and far from mature. Companies in countries with LIB production have a certain technical lead in developing recycling processes, as they have been able to develop their processes over a longer time period using production waste. However, most of these companies are also still adapting their processes. As a result, countries such as China and South Korea have a large LIB recycling industry, while Europe and the USA are somewhat lagging behind. African countries currently have no recycling industry for LIBs.

For recycling of LIBs, economies of scale are an advantage. That is, the larger the recycling plant, the higher the return on investment and the better the process can be designed. This is in particular true for the hydrometallurgical process. This last step at the end of almost every recycling process to recover the metals is complicated and requires access to sound management options for a wide range of chemicals and is most feasible on a large scale. To bridge the problem that full-fledged recycling facilities are not available in every country and world region, batteries either have to be shipped to recycling facilities, or undergo some partial treatment before shipment to further recycling[2]. This chapter looks into these options and describes models that have been suggested and/or tested in this context. The aim of this analysis is to identify feasible management options that may be realised under an e-waste compensation scheme in Nigeria. Although total end-of-life Li-ion battery volumes would undoubtedly justify a full-fledged recycling plant in Nigeria, the absence of collection systems and financing scheme (apart from the described e-waste compensation model and some B2B take-back arrangements) currently prohibit large investments in Li-ion battery recycling facilities, as access to sufficient waste volumes and return-on-investment are highly questionable[3].

While establishment of such recycling capacities are needed on the African continent in the mid- or long-term, partial treatment and export are already important stepping-stones

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[2] Alternative management options entail controlled disposal (e.g. hazardous waste disposal site, co-processing in cement kilns). Nevertheless, such options are – from a waste management perspective – clearly sub-standard compared to recycling and are not considered any further in this study.

[3] Also see chapter 5 on the economics of Li-ion battery recycling. Recycling facilities for Li-ion batteries can only be profitable when being compensated through gate fees or EPR funds. The value of the embedded materials is not enough to cover costs.

in this direction. They involve the building-up of necessary collection systems, as well as handling and processing capacities that are also required for full-fledged battery recycling.

In that context it should be stressed again, that reuse/repurposing is a meaningful way to manage used batteries that – as long as product safety can be guaranteed – should be given priority over recycling (see chapter 4.3). However, this option is only applicable to those batteries that still have reuse / repurposing potential. Furthermore, also reused / repurposed batteries will – at a certain point in time – reach their end-of-life requiring responsible end-of-life management solutions.

4.4.1 Export for recycling

As there are no treatment and pre-processing capacities in Nigeria or any neighbouring countries, an export of batteries to recycling is an obvious management option, also because shipment of other hazardous wastes for treatment is often seen as the only fully responsible management option for countries and regions with no treatment and disposal capacities.

Nevertheless, due to fire risks, shipment of end-of-life Li-ion batteries require very stringent safety and fire precautions. The most common approach is to pack Li-ion batteries in barrels filled with dry sand. In case of a thermal runaway of a battery cell, the heat is absorbed by the sand and prevents ignition of other cells. This management option was already conducted by Hinckley and CTL in the context of e-waste compensation in 2020 (see Figure 2) and proved to be associated with quite high costs. The main reason for these high costs is the quite unfavourable battery-to-sand ratio: In a container with a nominal load of 20t, this type of packaging only allows to ship 5t of end-of-life Li-ion batteries, which effectively means that the bulk of the shipment consists of packaging material, mostly sand (Closing the Loop 2020).

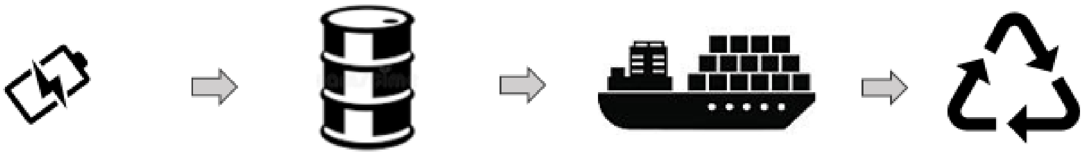
Figure 2: Loading of packed Li-ion batteries into a container for export

Source: Closing the Loop

Furthermore, a notification according to the procedures of the Basel Convention is required and a shipping company willing to accept a container filled with LIBs must be found. While the latter point was still possible in 2020, recent information given by shipping agencies suggest that waste Li-ion batteries will not be accepted on the transport route from West-Africa to Europe anymore.

Further economic assessments are discussed in chapter 5.

Overview Export for recycling



Short description	Collected EoL Li-ion batteries are embedded in dry sand and packed in drums for export to recycling.
Investment costs	Low (packaging material, handling & storage space)
Output material	Packed batteries for shipment & recycling
Status of output material	Hazardous waste
Further aspects	▪ High operational costs (shipment) ▪ It is difficult to find off-takers for cobalt free Li-ion batteries (also see Table 1). ▪ Increasing reluctance of shipping agencies (fear of fires on ships and in ports…).

4.4.2 Manual pre-processing

Li-ion batteries with high cobalt content are reported to be manually processed to recover the aluminium and copper foils including the active materials (black mass) as pure output fractions for further treatment. Next to various literature indications (Marshall et al. 2020; Pagliaro and Meneguzzo 2019), the existence of such manual operations is also supported by evidence from plant visits in countries with cheap and abundant labour force (see Figure 3). While the existence of such processing is not proven for Nigeria, there are some indications that related processes are conducted in the country[4].

Manual dismantling and separation yields copper foils (current collectors) coated with graphite, binder and carbon black, as well as aluminium foils coated with active material such as lithium cobalt oxide, binder and carbon black. Apart from the electrode foils, the process will also create a fraction of separators and cell housing, all of which can be treated separately. This is the main processing advantage as it allows a more specified treatment and recovery of more materials with higher purity.

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[4] From the project's collection efforts, it is known that other collectors are also interested in collecting EoL mobile phone batteries. Based on economic considerations, it appears likely that this collection is tied to low standard manual dismantling processes and export for further treatment (probably without valid notification in-line with the Basel Convention).

Figure 3: Electrodes (mainly graphite on copper foil) from manual LIB dismantling

Source: Mountain Research Institute

While manual dismantling is technically possible, it provides various health and safety challenges, including:

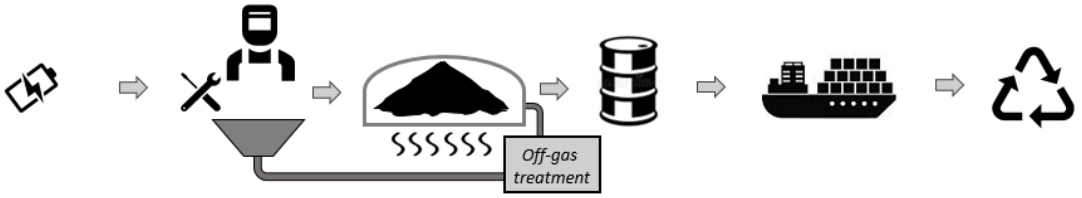
- Electrical shocks from residual charge (strongly depending on battery size)
- Fire & explosion risks
- Risks from contact with solvents and acids
- Risks from exposure to dust with hazardous properties

On a laboratory scale, safe manual dismantling can be achieved for small batteries (e.g. cells of mobile phones) by using glove boxes, extraction ventilation linked to an off-gas treatment system and proper safety equipment. Nevertheless, glove boxes are usually not suitable for continuous operation, as it is ergonomically difficult to work in them and they require a lot of maintenance.

Therefore, continuous operation must use alternative means for healthy and safe operations and must ensure that workers do not get in contact with or inhale any battery material / chemical. Furthermore, workers must be effectively protected from electrical shocks and fire risks, which, however, also applies to any other dismantling of LIBs prior to pre-treatment. Manual dismantling should also be followed by heating of the produced material to evaporate and capture the electrolyte. Additional safeguards must be in place to avoid emissions of dust and fumes to the workplace and the environment.

Such a system set up is not known to exist yet, so that a related approach would require investments in research and development, including thorough workplace exposure monitoring. In that context, the feasibility of high standard manual pre-processing is still in question and likely to be less effective than other pre-processing approaches.

Overview Manual pre-processing



Short description	Collected EoL Li-ion batteries are dismantled manually and separated into main constitutes, namely the electrodes (consisting of coated copper and aluminium foils), cell housing and separator.
Investment costs	Unknown, as there is no known manual process for industrial recycling purposes that effectively protects workers from all associated hazards.
Output material	Copper and aluminium foils, each coated by different material (black mass), separators, cell housing
Status of output material	Hazardous waste, but not flammable or explosive
Further aspects	▪ High standard manual pre-processing is not an established concept (so far only evidence for sub-standard operations). ▪ Effective health and safety measures needed, which includes (but might not be limited to): P100 respirators, eye protection, neoprene or nitrile gloves, extraction ventilation, off-gas treatment. ▪ It is difficult to find off-takers for black mass from cobalt free Li-ion batteries (also see Table 1).

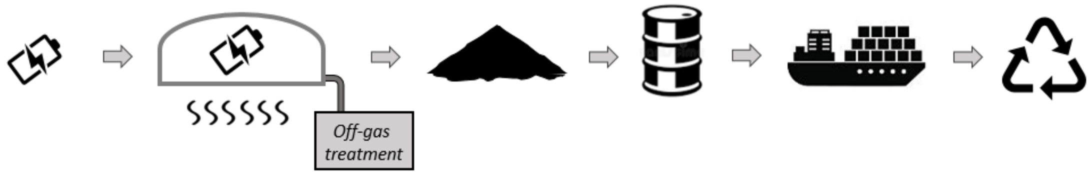
4.4.3 Thermal pre-processing

Thermal pre-treatment has several objectives. Firstly, the battery cell is deactivated by decomposing the electrolyte and disabling the active materials, resulting in a material that can be transported relatively safely in closed containers. Secondly, it destroys the polymeric binders in the electrode. The binders hold the electrode together and keep the black mass on the current collectors. Separating them mechanically without prior thermal treatment is very difficult. Therefore, thermal treatment at some point is part of most industrial-scale recycling processes. Even in processes where the battery is first shredded, the battery is often then heated to remove the electrolyte, usually at the same time deactivating the binder at a certain temperature.

To deactivate only the cell, temperatures above 250 °C can already be sufficient (Georgi-Maschler et al. 2012; Sommerville et al. 2021). These usually cause the cells to burst open and the organic solvents of the electrolyte to evaporate. Temperatures between 400 and 600 °C are usually used to remove the electrolyte, binder and separator (Sommerville et al. 2020). The heat treatment is usually carried out under inert gas (nitrogen, carbon dioxide or argon) or vacuum conditions, as otherwise an explosive atmosphere can develop (Sommerville et al. 2020). Extensive off-gas treatment must also be installed to treat the gases produced, including hydrofluoric acid and various toxic organic substances. In addition, the evaporated solvents must be collected and treated as well. The resulting hydrofluoric acid also poses a challenge for the interior of the oven, as it must be specially designed for the corrosive mixture (Sojka et al. 2020).

Thermal pre-processing is therefore connected to high investment costs due to the specially designed oven and the extensive emission treatment system. Another challenge is the sound disposal of waste streams resulting from gas treatment. This process is also high-maintenance and energy-intensive, needing a stable power supply over a long period of time. Without proper care, the process can be very dangerous, as the inert atmosphere must be controlled constantly and the emission treatment has to work properly during all hours of operation. The ruptured batteries have to be handled with care, as the insides of the batteries are released, which are toxic. Dust generation due to the dry state of the pre-treated batteries is possible and exposure of workers must be avoided. Therefore, this management option is only feasible for a large stream of LIBs, especially with higher temperatures, questioning the practicability of thermal pre-processing in Nigeria.

Overview Thermal pre-processing



Short description	Collected EoL Li-ion batteries are heated in an oven in inert atmosphere.
Investment costs	High, no prototypes available
Output material	De-activated battery cells, including some hazardous constituents
Status of output material	Hazardous waste, but not flammable or explosive
Further aspects	▪ Off-gas treatment is considered to be quite complex requiring effective capture of dust, acids, and organic compounds. ▪ It is difficult to find off-takers for black mass from cobalt free Li-ion batteries (also see Table 1).

4.4.4 Mechanical pre-processing

Mechanical pre-processing is currently the most commonly followed way of Li-ion battery pre-processing with various equipment manufacturers developing and offering solutions of different sizes and capacities. Typically, mechanical pre-processing entails dismantling of larger batteries, shredding of cells and separation of black mass, a powder, which includes only the active material of anode and cathode (containing e.g., cobalt, nickel, lithium, manganese or graphite, etc.), carbon black, binder, and electrolyte residue. While separation of black mass, aluminium, copper and plastics is part of most solutions, it is also possible to pack and ship unsorted shredded batteries for further processing abroad, which may allow a slight reduction of investment costs.

As mechanical pre-processing is scalable in terms of capacities, it can be an attractive option for smaller recycling facilities. Nevertheless, not all offered equipment has been tested and run over prolonged time periods so that practical experiences are often limited.

In addition, mechanical pre-processing of LIBs is connected to several challenges, especially concerning safety. There are two main technologies, dry and wet shredding, first described and then compared with each other, listing the benefits and disadvantages. They both serve the crushing of battery cells to separate the components afterwards and produce the black mass. The material of highest economic interest in this mixture is the cathode active material, as it can contain cobalt and nickel, depending on the cell chemistry (also see section 5.2). Apart from the black mass, the materials resulting from a shredded battery also include plastic parts (e.g. the separator), current collectors (aluminium and copper foil) and the cell housing.

The shredder itself should reduce the battery parts in size below 2 cm, however, not pulverize the material, as this makes it difficult to separate the various materials afterwards. Shredding itself will not lead to the perfect separation of black mass and current collectors without additional treatment before or afterwards, as the binders as part of the electrode keep them together.

4.4.4.1 Dry shredding

Dry shredding should take place under an inert atmosphere and only be conducted on completely discharged LIBs, as it can otherwise lead to explosions. This is due to the residual energy in the batteries set free at once and the organic electrolyte, which can lead to explosive atmospheres when mixed with oxygen. To create this inert atmosphere, usually nitrogen is used. This atmosphere has to be well monitored, as an oxygen content above 6 % causes immediate explosion risks. The shredder should have a monitoring function such as an oxygen sensor. Furthermore, the atmosphere resulting from shredded batteries is highly corrosive, which alters not only the blades of the shredding equipment, but especially the seals used to contain the inert atmosphere. This is also the reason for the necessity of special materials covering the inside of the shredder and a warranty that these materials can withstand the corrosive atmosphere over time.

For safe dry shredding, LIBs are ideally fully discharged prior to treatment. But complete discharging of the LIBs is also not simple. So far, there is no reliable solution for discharging all LIB formats without thermal treatment (see chapter 4.4.2). Often, a battery management system (BMS) prevents a complete discharge, as this process damages the LIB during general use. However, small LIBs usually do not have a BMS. A saltwater bath can only discharge LIBs to a certain degree, as the electrical contacts corrode very easily. This is especially the case with pouch cells and their electrical contacts, which are mostly used in mobile phones. Another option would be to connect the LIB to a resistor to slowly discharge it. This takes time, space, and effort, but could work for most cell formats, if the contacts are not removed. Direct short-circuiting of a cell as alternative is very dangerous and leads to fires and similar consequences.

Even when the cells are discharged before and the inert atmosphere is well surveyed, dry shredding is not without risks or safety hazards. This mainly results from remaining electrolyte, particularly the volatile species of the organic solvents. Therefore, the dry shredding process should be followed by a process where the material (shredded LIBs) is heated to evaporate and capture the electrolyte.

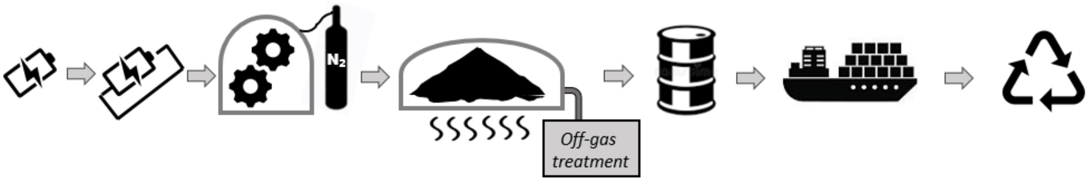
As mentioned before, the heating process has to be completely sealed off and all generated gases evacuated and captured. A lower pressure (vacuum) can help to evaporate the electrolyte more easily and decrease the necessary temperatures. As discussed earlier, heat treatment can be used to deactivate the binder to allow separation of the black mass from the current collectors (aluminium and copper foils respectively). Without heat treatment, an impact reactor is needed for a high degree of separation. This is, however, very expensive equipment. Without the vacuum, the shredded materials can still react, especially, if the discharge of the cells was not complete and there is still, e.g. lithiated graphite left, which can react with any humidity. Another safety hazard is the resulting black mass. In dry form, it can easily become airborne and be inhaled. As it is toxic, this scenario must be avoided at all costs. Therefore, leaving shredded material to dry in the air for long periods of time is not a safe option.

4.4.4.2 Wet shredding

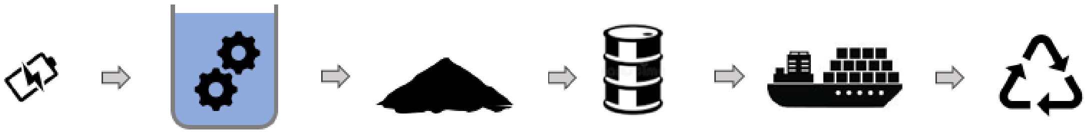
Wet shredding on the other hand uses water to deactivate the cell during the shredding process. Nevertheless, for wet shredding, the cells should be discharged as well to avoid too much build up of hydrogen, which could form an explosive atmosphere, if not dispersed fast enough. Furthermore, the water of the shredding process has to be made alkaline, to protect the shredding equipment from the acidity of the battery chemicals. A possible solution could be calcium hydroxide ($Ca(OH)_2$), which also helps to reduce the fluoride content. The process water itself could pose a problem, as it will be enriched with organics. However, when separated from the battery materials by filtration, it can be used again. A significant part of the water will remain part of the black mass and could be exported with it, ideally resulting in a process without wastewater generation. An evaporation step for the electrolyte should not be necessary before shipping, but a packaging investigation must be carried out to see how the material actually behaves when subjected to higher temperatures inside a shipping container exposed to the sun. It is a clear advantage to be able to reduce dust formation due to the wetness of the material.

Overview Mechanical pre-processing

Dry shredding



Wet shredding



Short description	Collected EoL Li-ion batteries are discharged and fed into a shredder that is kept under inert atmosphere (e.g. nitrogen). The generated material is heated to deactivate the binder and evaporate the electrolyte solvent, which is absorbed in an active carbon filter. The resulting material is packed in drums and can be exported for end-processing. Further (local) value addition may include separation of black mass, copper and aluminium foils prior to packing and shipping. The process for wet shredding differs in the shredding process, which is conducted under alkaline water to reduce the danger posed by the batteries and deactivate the resulting material. An evaporation step should not be necessary, but a packaging investigation must be carried out.
Investment costs	US$ 100,000 – 1,500,000
Output material	Shredded batteries (mix of black mass, copper foils, aluminium foils and plastics). In case a sorting step is added, 5 distinct output fractions (black mass, copper, aluminium, plastics, cell housing).
Status of output material	Shredded batteries and black mass are hazardous waste. In some countries (e.g. Canada) wet black mass is not considered hazardous waste.
Further aspects	▪ No solution for full and reliable discharging of batteries available yet. ▪ Dry shredding processes involve generation of dust with hazardous properties. Therefore, dust control is a crucial element of plant operation (in addition to managing fire and explosion hazards). ▪ Wet shredding processes yield wet/moist output material effectively minimizing dust generation risks. But wet black mass might also limit the number of potential off-takers for the black mass. ▪ Wet shredding requires sound wastewater management. ▪ It is difficult to find off-takers for black mass from cobalt free Li-ion batteries (also see Table 1).

4.4.5 Pyrometallurgical processing

EoL LIBs can also be treated in a pyrometallurgical furnace without prior pre-treatment[5]. In the furnace the batteries are exposed to heat > 1000°C so that organic materials are burned and metals smelted into an alloy (Zhou et al. 2020; Sojka et al. 2020). Although exposure to heat causes batteries to catch fire and explode, risks can either be mitigated by a staged temperature sequence, or a massive design of the furnace combined with a strategy of feeding only smaller battery batches at a time[6]. In terms of furnace technology, different types and designs are used. For the purpose of this project, a small versatile model is described that is currently used by Ecomet Refining, Italy, as well as some other recyclers in Europe, North America and India. The furnace used is a tilted rotary furnace with oxygen enrichment (Ecomet Refining 2016). Pre-heating is done with a gas burner (methane, butane or propane). Once feeding has started, gas supply can be reduced or stopped as the organic material of the batteries have enough calorific value to

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[5] Dismantling might be required or useful for larger battery packs that – due to size constraints – cannot be fed to the furnace as they are. Dismantling can also be useful to pre-separate certain components such as cables and circuit boards and deliver them to separate, more suitable recycling routes.

[6] For additional safety, feeding should be done with a sledge or a similar system that does not require any operator close to the feeding port.

sustain the smelting process. In addition to batteries, a silica-containing material (glass, sand) must be added as flux agent[7].

Figure 4: Feeding port and off-gas treatment system of a pyrometallurgical treatment plant for Li-ion batteries

Source: Ecomet Refining

The molten metal is poured into holding kettles by tilting the furnace. In the kettles, the metal and slag can cool and solidify. The slag accumulates on top of the metal alloy and can be removed manually after cooling. The alloy mainly consists of copper with other elements such as cobalt and nickel. The slag is a silica-aluminium-iron compound with some embedded elements in lower concentrations such as lithium[8]. While the alloy can be shipped for further processing in a refinery, the slag must undergo a leaching test. In case the test does not indicate any environmental hazards (no leaching of heavy metals) it can be disposed of or used in road construction[9]. Alternatively, the slag can be sent to a specialised Li-recovery process, but this is likely to generate additional net-costs[10] (Windisch-Kern et al. 2021).

The off-gas from the furnace (including extraction ventilation for feeding and tapping port) must be treated in various steps, including a) after-burner to destroy organic pollutants, b) baghouse dust filter and possibly c) lime-dosing to prevent acidic emissions.

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[7] This may open opportunities to process smaller quantities of glass from e-waste (e.g. liquid crystal display layers, CRT-glass, PV-modules)

[8] The exact compositions of slag and alloy depend on the type and composition of furnace feed: While aluminium, iron and some trace metals such as lithium go into the slag, copper, lead, cobalt and precious metals form the alloy.

[9] Silica slag is commonly inert with a high likelihood of negative leaching tests. In case the leaching test is positive (leaching of hazardous compounds), the slag must be treated as hazardous waste and processed/disposed accordingly.

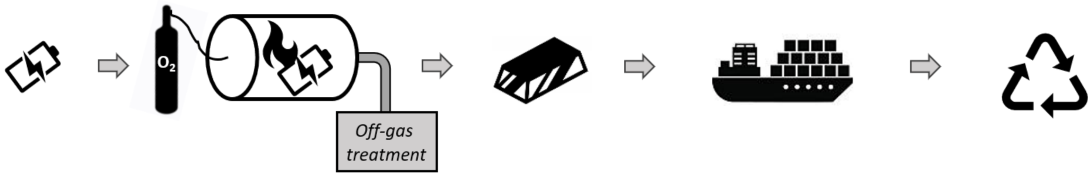
[10] There are companies developing processes to recover the lithium from the slag of recycled Li-ion batteries. However, due to high costs this is not a standard process yet. This may change in the future or will become a mandatory requirement in some jurisdictions.

While this processing technology can process all types of Li-ion batteries and convert them into a commodity that can be shipped without Basel Convention notification, the process also eliminates possibilities to recover graphite and aluminium in later process stages: While graphite is burned and converted to CO_2, aluminium goes to the slag from where recovery is more difficult than from primary aluminium deposits (bauxite).

The furnace technology and process can also be utilised to process other copper and precious metal containing scraps (e.g. printed circuit boards, industrial catalysts).

In terms of operation, smelting processes should only be conducted in industrial zones and by experienced operators. Next to the smelting process and off-gas treatment, the use of elementary oxygen requires adequate safety precautions and routines. In terms of maintenance, the refractory lining of the furnace requires regular renewal (e.g. around once per year), which must be done by a specialised company. The formation of hydrogen fluoride (HF) if not treated can cause corrosion to various system elements.

Overview Pyrometallurgical processing



Short description	Collected EoL li-ion batteries are fed into a smelting furnace fuelled with gas and oxygen (gas to ignite the process, plastics and organic materials of the batteries can add to the required smelting energy). Electrolyte and carbon-containing material are burned and metals smelted. The produced copper alloy can be shipped for refining.
Investment costs	US$ 2,000,000 – 3,000,000
Output material	▪ Copper alloy with other embedded metals (e.g. cobalt, nickel) ▪ Silica slag (mainly Si, Fe, Al)
Status of output material	▪ Copper alloy: Commodity ▪ Silica slag: In case of negative leaching test (no leaching of hazardous compounds), non-hazardous waste
Further aspects	▪ Off-gas treatment must entail a) afterburner to avoid emissions of organic pollutants b) dust filter and possibly c) lime dosing to avoid acidic emissions

4.4.6 End-processing

As discussed in the beginning of chapter 4.4, there are various recycling processes for LIBs, but most of them need a hydrometallurgical step at the end to recover metals like cobalt and nickel. This step, however, needs large amounts of materials to be feasible and requires a high technological level and infrastructure, including supply and sound end-of-life management systems for multiple process chemicals in large volumes. As the quantities of batteries collected are still insufficient, attempting to establish such a process step in Nigeria does not appear feasible at present.

4.5 Management of other battery types

When collecting portable LIBs, there is always the possibility that other batteries such as NiMH or Ni-Cd will also be collected. The management options for NiMH and Ni-Cd batteries at their EoL are comparably simple, as there are no safety issues that necessarily require pre-treatment in Nigeria, allowing shipment to further processing abroad. Especially Ni-Cd batteries should not be shredded or smelted, as cadmium is highly hazardous likely leading to toxic emissions and corruption of resulting material outputs. Therefore, Ni-Cd cells have to be separated out very thoroughly, as only one wrongly sorted cell is likely to lead to unacceptable emissions in the subsequent treatment processes for LIBs.

After sorting, they can be exported to a place where they can be recycled. While NiMH batteries have a certain material value and can be sold at a premium, the proper recycling of Ni-Cd batteries costs more than the resulting resources can compensate, as cadmium is very toxic resulting in high efforts and costs for emission controls. While the transport of Ni-Cd batteries across national borders has to be notified under the Basel convention, NiMH batteries may be green-listed by some countries but are also considered as hazardous waste by others.

5 Economic aspects

The economics of LIB recycling depends on the various factors:

- Costs for the collection, handling, storage, pre-processing and shipment
- Costs or revenues from final treatment (gate fees for recycling)
- Payments from contract partners (e.g. payments from e-waste offsetting partners, disbursement of EPR fees)

These aspects are briefly examined in the following sub-chapters.

5.1 Collection, handling, storage, pre-processing, and shipment

The exact cost structure associated with collection, handling, storage, and shipment of (processed or unprocessed) LIBs is currently difficult to assess as full environmentally sound management in the Nigerian context is still a new field and the costs of recycling LIBs are changing constantly.

Collection of batteries is associated with costs. Normally collection costs would be covered by the waste generator or through an EPR scheme. In the absence of these, it is possible to work with existing collection networks (formal or informal) which are used to being paid upon delivery of the material. Thus, collection must work with incentives as done in this pilot and as suggested in various other projects and pilot collection schemes (Manhart et al. 2020; Blair et al. 2021). Depending on the framework conditions, this results in collection costs of around 0.75 to 1.5 €/kg of batteries.

As illustrated in chapter 4 investments in storage facilities, packaging material, as well as development of processes and routines is also required, which is associated with potentially significant costs. In 2020, CTL and Hinckley exported 5 t of mobile phone batteries from Nigeria to Belgium and indicated that the total project costs for this effort exceeded 70,000 € (Closing the Loop 2020). These costs may significantly be reduced by probably 90 % as further efforts can draw from collected experiences and processes, and as that figure also contains R&D costs. Subsequently, costs for handling, storage and shipment (not including collection) would still be at around 1.4 €/kg. This figure corresponds well with prices charged by formal recycling companies in various African countries that range between 0.60 and 2.53 US$/kg[11] (Magalini et al. 2020).

Nevertheless, shipment of untreated batteries has become very difficult or even impossible in the Nigerian context (see section 4.4.1) so that additional local pre-processing is required. Investment costs for mechanical pre-processing (dry) are likely to be between 100,000 – 1,500,000 € provided the system is designed for relatively small battery quantities (100 – 500 t/a). Assuming the system is used for a total volume of 1000 t, the investment costs would break down into 100 – 1,500 €/t, not considering interest payments. It needs to be mentioned that this is a rough estimate only, and key factors (the combination of investment costs and total treatment volumes per system) are subject to speculation as experiences with this kind of treatment are still limited (see section 4.4.3). In any case, it is assumed that cheaper equipment will also fail earlier so that a

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[11] Although the figures were collected from various registered recyclers in African countries, they have to be treated with some care as very few of these players have established environmentally sound end-of-life management solutions of LIBs. Therefore, some elements of these figures are likely to be based on feasibility studies rather than on established cost structures or might refer to second-best management options such as controlled disposal.

value of 800 €/t is used for further calculations. In terms of operational costs, 400 €/t are assumed[12], resulting in total pre-processing costs of 1200 €/t (1.2 €/kg).

While such pre-processing leads to higher costs, it also reduces packaging efforts for shipment: While unprocessed LIBs require a quite unfavourable LIB to packaging ratio (see section 4.4.1), this can be considerably improved with shredded batteries, reducing total costs for handling, storage and shipment to 0.9 €/kg.

Total costs for collection, handling, storage, pre-processing and shipment are therefore estimated at 2.85 - 3.6 €/kg.

5.2 Final treatment

There are various sub-types of lithium-ion batteries, which all have different properties and material compositions (see Table 1).

Table 1: Major LIB sub-types and their properties

Battery chemistry		Properties
LCO	Lithium-cobalt oxide	▪ Mostly contain cobalt (up-to 25 %) ▪ High energy densities ▪ High purchasing price ▪ Mostly used in mobile applications (portable electronics, electric vehicles)
NMC	Lithium-nickel-manganese-cobalt oxide	
NCA	Lithium-nickel-cobalt-aluminium oxide	
LFP	Lithium-iron phosphate	▪ No cobalt (0 %) ▪ Lower energy densities ▪ Lower purchasing price ▪ Mostly used in stationary power storage, electric buses, and lower range electric vehicles)
LMO	Lithium-manganese oxide	

Source: Own compilation

The material compositions have a high implication on the economics of recycling. Cobalt is the main value carrying material with global market prices ranging between 25,000 and 95,000 US$/t between mid-2016 and mid-2021 (Trading Economics 2021). Recyclers also recover copper, nickel and – depending on the applied processes – also aluminium, manganese and lithium. Nevertheless, recycling process are quite complex so that treatment costs may surpass the value of recovered raw materials. Table 2 uses annual averages of the world market prices for cobalt, nickel, as well as the US$-Euro exchange rates to model average price levels for EoL LIBs, applying the most recent costing calculation tool by Accurec (ACCUREC Recycling GmbH 2021).

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[12] Capacity: 100 t/a; maintenance costs: 2.5 %/a; salaries: 10,000 €/a; electricity, chemicals etc.: 100€/t.

Table 2: Calculation of indicative EoL LIB prices using historic raw material prices and exchange rates

	2016	2017	2018	2019	2020
Cobalt price [US$/t]	25507	55733	72620	32805	30865
Nickel price [US$/t]	9594	10403	13114	13903	14000
US$-€ exchange rate	1.1069	1.1297	1.1810	1.1195	1.1422
LCO-price [€/t]	419	433	279	69	186
NMC-price[13] [€/t]	-1650	-1650	-1650	-1650	-1650
LFP & LMO-price [€/t]	-2000	-2000	-2000	-2000	-2000

Source: Calculated with data from (USGS 2021a; 2021b; Deutsche Bundesbank 2021; ACCUREC Recycling GmbH 2021)

The data shows that only LCO batteries yield positive returns, while NMC, LFP and LMO batteries are subject to considerable recycling fees[14].

The values apply to unprocessed battery deliveries. In case of pre-processed LIBs (see section 4.4) different price levels may apply. Nevertheless, the general picture (some positive returns from shredded LCO-batteries, considerable processing fees for shredded NMC, LFP and LMO batteries) is likely to be similar.

5.3 Payments from contract partners

As illustrated in sections 5.1 and 5.2, collection, handling, storage, pre-treatment, shipment and final recycling of EoL LIBs is associated with significant costs that range between 2.7 – 3.45 €/kg for LCO batteries, 4.5 – 5.25 €/kg for NMC batteries and 4.85 – 5.6 €/kg for LFP and LMO batteries when applying mechanical pre-treatment (see Table 3). While these cost figures are indicative only and may deviate depending on the type of chosen processes, equipment and scale of operation, it appears highly unlikely that processing and recycling can generate enough material value to fully finance environmentally sound recycling. This means that environmentally sound recycling as sketched in this study requires additional financing covering these costs and allowing some profit for the involved actors.

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[13] Most likely including similar chemistries such as NCA.

[14] Note: The data presented in Table 5 2 uses a price modelling tool valid for 2021 only. In the years prior to 2021, real prices might have been slightly different as recycling processes and price calculations evolved over time. Nevertheless, the calculation yields values that give an impression how changes in raw material prices and exchange rates can influence EoL LIB prices.

Table 3: Overview over the cost structure for EoL battery processing depending on the cell chemistry

	LCO	NMC	LFP	LMO
Collection	-0.75 to 1.5 €/kg	-0.75 to 1.5 €/kg	-0.75 to 1.5 €/kg	-0.75 to 1.5 €/kg
Pre-processing	-1.2 €/kg	-1.2 €/kg	-1.2 €/kg	-1.2 €/kg
Handling, storage & shipment	-0.9 €/kg	-0.9 €/kg	-0.9 €/kg	-0.9 €/kg
Final treatment	+0.15 €/kg	-1.65 €/kg	-2.00 €/kg	-2.00 €/kg
Sum	-2.7 to -3.45 €/kg	-4.5 to -5.25 €/kg	-4.85 to -5.6 €/kg	-4.85 to -5.6 €/kg

Source: Assessments of sections 5.1 and 5.2

5.4 Policy development in Nigeria

Policy development on waste batteries is advancing in Nigeria, and a legislative framework consisting of a battery policy and regulation has been drafted (NESREA 2022, Nigerian Federal Ministry of Environment 2021)[15]. Once the National Environmental Battery Control Regulation is commissioned, Extended Producer Responsibility (EPR) will become mandatory for all types of batteries placed on the Nigerian market. The National Waste Battery Management Policy complements the regulation with a roadmap of foreseen activities and (collection & recycling) targets for the next few years.

Although EPR for batteries is not yet mandatory, there is a Producer Responsibility Organization (PRO) that already started the collection of end-of-life batteries. This PRO is named Alliance for Responsible Battery Recycling (ARBR) and so far predominantly focuses on used lead-acid batteries (ULABs). According to its management, ARBR collected around 6,000 tons of used lead-acid batteries in 2021 and channeled them to their registered recyclers. At the moment, some of the commissioned recyclers are still operating below best practices. These entities are classified by ARBR as being in ‘transition phase’ and will be supported to reach minimum technical standards in the future (Ugbor 2022). 6,000 tons of waste lead-acid batteries represent around 3-5 % of the total annual generation in Nigeria, which is estimated to range between 110,000 – 200,000 tons (Ugbor 2016). It is planned to expand activities to Li-ion batteries, but this has not yet been rolled-out.

Batteries from mobile phones are also covered through e-waste related policy making. Policy-development has already started with the National Environmental (Electrical/Electronic Sector) Regulation of 2011 (Nigerian Federal Ministry of Environment 2011), which included provisions for an Extended Producer Responsibility Programme. Nevertheless, a financing system through an EPR mechanisms is just being built up, supported by a recently published Guidance Document for the Implementation of the Extended

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[15] At the current stage, the battery policy and regulation are available as finalized drafts, which need to undergo last administrative steps before being commissioned.

Producer Responsibility (EPR) Programme for the Electrical /Electronics Sector in line with Circular Economy (NESREA 2021). In this document, mobile phones are listed as one out of five product groups to be of immediate priority and to be addressed by short term collection and recycling activities.

A PRO for the environmentally sound end-of-life management of e-waste has been established but is not yet fully operational and no EPR fees are raised yet. The PRO is named Environmental Producer Responsibility Organization Nigeria (EPRON) and its membership base comprises some of the biggest producers. Additionally, EPRON has registered collectors and recyclers, which are supposed to provide sound end-of-life management once EPR implementation goes beyond registration. A standard defining minimum criteria for sound management and for benchmarking collectors and recyclers is currently being developed. Additionally, EPRON works on a set of differentiated fees, covering the costs that actually arise from sound end-of-life management of different types of e-waste. Furthermore, a software supporting the PRO´s administrative processes is under development.

At this point in time, PRO-driven collection and recycling activities are limited to pilot testing, and participating producers do not yet pay EPR fees for their product volumes placed on the Nigerian market. Thus, the e-waste EPR system is still in a quite initial stage with no established routines in fee collection, administration and organisation and monitoring of collection and end-of-life management of e-waste.

An additional challenge described by both PROs is to keep track of the amounts of goods brought to the Nigerian market. They are working on suitable tracking solutions together with Nigerian customs, the Standard Organization Nigeria (SON)[16] and the responsible enforcement authority (NESREA).

Summarizing, this means that there is not yet a functioning structure that fully finances environmentally sound management of end-of-life Li-ion batteries from mobile phones. In this situation, end-of-life Li-ion batteries are still subject to unsound management as costs for full responsible management are not covered.

In this context, piloting the concept of e-waste compensation in Nigeria was welcomed by various stakeholders engaged in the development of the mentioned policies and EPR systems. While it is clear that e-waste compensation cannot replace any binding national policies and financing mechanisms, it can serve as a first case where (monetary) contributions enable full responsible collection, handling and management of EoL Li-ion batteries. With this, collection networks, recyclers and responsible authorities gain practical insights in developing high standard management, from a technical, logistical, and a financial perspective. However, the aspect of additionality needs to be respected carefully to avoid double accounting of collected and managed volumes particularly when national EPR schemes become operational in Nigeria (see section 2). Experts involved in the set-up of EPR systems expressed their high interest to receive an overview of practical learnings from piloting e-waste compensation for Li-ion batteries in Nigeria and stressed the importance to continue coordination efforts from both processes in the future.

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[16] SON has developed standards, which include requirements for new products coming to the Nigerian market. Currently, these SON standards do not cover used products.

6 Summary and way forward

Despite significant volumes of EoL Li-ion batteries, there are only very few starting points for collection and management of EoL Li-ion batteries in Nigeria so far:

- Some informal networks collect end-of-life Li-ion batteries from mobile phones (high cobalt content), presumably for manual recycling and export of dismantled batteries. No details around these practices are known, but – based on economic considerations – it is likely that related processes expose workers to hazardous substances from the batteries.
- Some solar companies collect dysfunctional warranty equipment and supply it to registered recyclers for treatment. These arrangements primarily yield batteries with low cobalt content (e.g. LFP-batteries), which are quite unattractive for recycling. On the other side, some of the battery cells are still functional and may be used as feedstock for reuse and repurposing activities.
- Reuse and repurposing are also conducted by small local repair shops offering products such as low-price power banks from used batteries.

Without a change in framework conditions, this causes a situation where some reuse and repurposing might extend the life-time of some batteries, but where EoL batteries are either recycled with sub-standard processes (only those with high cobalt content) or disposed together with other municipal solid waste (dumping, landfilling), generating fire risks in waste disposal sites, as well as release of hazardous substances.

Advancing policy development, including plans to introduce mandatory EPR systems for batteries and e-waste may change this situation in the future. To date, the most tangible developments are the formation of two PROs – one on batteries, one on e-waste. While the battery-related PRO focused its activities on used lead-acid batteries so far, the e-waste PRO is – apart from conducting pilots of limited scale – not yet operational. Thus, their activities do not yet influence the collection and management patterns for EoL Li-ion batteries. Nevertheless, their mandate and scope of operation is likely to have positive impact on EoL management landscape in Nigeria in the future and should therefore be supported.

E-waste compensation offers the opportunity to pilot full environmentally sound management of EoL Li-ion batteries from mobile phones and to develop tangible lessons-learned for existing policy-development and implementation. While this opportunity can be an important step for advancing the country’s formal and high-standard e-waste management landscape, this project revealed various hurdles that make it difficult to implement and roll-out full responsible Li-ion battery recycling in Nigeria at this point in time:

- Due to various incidents of fire outbreaks, shipping agencies are currently extremely reluctant to accept freight with waste Li-ion batteries. Thus, the export of unprocessed Li-ion batteries is currently difficult or even impossible under legal and transparent business conduct.
- Local pre-processing requires investment in equipment indicatively ranging between 100,000 and 3 million US$, with the cheaper equipment being less versatile, and probably less reliable and safe. While Nigeria hosts enough EoL battery volumes for such investments, the absence of collection systems and financing models presents a major obstacle.

- The latter point goes back to the fact that sound battery processing is associated with net costs. While Li-ion batteries contain various raw materials (e.g. copper, nickel, cobalt), costs for collection, pre-processing, handling, storage, shipment and recycling clearly exceed the revenues from raw material recovery. Therefore, the use of high standard recycling equipment is tied to the battery volumes of which full environmentally sound management is financed through fees paid to recycling companies.
- While Closing the Loop is such a company capable and willing of paying for high-standard recycling, financial capacities are insufficient to finance the required investments alone.

In order to bridge these gaps, the following strategy is recommended:

- As a first step, a dialogue with shipping agencies should be initiated trying the lift the indiscriminate ban of EoL Li-ion battery shipments. While safety concerns of shipping agencies should not be ignored, the following line of argumentation might help to soften their position:
  - While Li-ion batteries are dangerous goods, sound packaging and safety requirements can effectively mitigate fire risks during transport. Rather than imposing indiscriminate bans, shipping agencies should support effective packaging and safety protocols for such shipments and make sure these protocols are properly implemented.
  - This is also needed because an indiscriminate ban might lead to false declarations of EoL Li-ion, which are likely to increase the fire and safety risks even further.
- In parallel, investments in and set-up of processing infrastructure for Li-ion batteries should be supported. Such support can focus on 2 aspects, namely a) the development of battery collection and EoL financing systems, b) direct investment support.

For developing of battery collection and EoL financing systems, the following steps are recommended:

- Align with donors, projects, and companies active in the solar offgrid sector. This sector is often pioneering sound EoL management and might be willing to support battery collection within their spheres of operation. Comparable strategies might be applied with other battery using sectors such as telecommunication[17]. By pooling EoL batteries from various sectors and from e-waste compensation models, volumes (and associated end-of-life management financing) might be sufficient to justify investments in local treatment capacities.
- Cooperate with the newly founded Producer Responsible Organisations (PROs) *Alliance for Responsible Battery Recycling (ARBR)* and *Environmental Producer Responsibility Organization Nigeria (EPRON)* to establish an effective collection and financing mechanism based on the principle of EPR.

For supporting direct investments in processing capacities:

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[17] Batteries collected through other systems shall not be accounted for in e-waste compensation models. Nevertheless, combining the various collection volumes can help to achieve critical minimum volumes for establishing treatment capacities.

- Develop a business plan, including a detailed description of technology options, available battery volumes and sub-types, and realistic collection volume scenarios under the given financial conditions.
- Identify suitable locations (in industrial zones) and ownership and management structure of facility.
- Present this business plan to potential investors, including donors potentially capable of match funding.

In terms of the described treatment options, export for recycling (section 4.4.1), mechanical pre-processing (section 4.4.4) and pyrometallurgic processing (section 4.4.5) appear to be the most feasible options for the Nigerian context. For further decision-making, the following aspects should be considered:

- Export for recycling is currently very difficult or even impossible (see above). In case this option will be available again, it should be considered that implementation is associated with high operational costs and does not lead to investments in processing / value addition in Nigeria. But it is certainly the only option that allows a full responsible management of batteries under small-volume and low-investment conditions.
- Mechanical pre-processing can be done with a wide range of offered equipment. Some of this equipment was just recently developed and has not yet been tested under prolonged real-life conditions. Safety, emission control and reliability are not necessarily guaranteed with such equipment. Furthermore, mechanical pre-processing is likely to be insufficient for batteries with low cobalt content (LFP batteries used in many solar installations) as the generated black-mass will likely not find off-takers.
- Pyrometallurgical processing requires substantial investments (2-3 million Euro) but is the most versatile solution as it can treat all types of Li-ion batteries and also other types of waste (e.g. circuit boards from e-waste, display glass…). A further advantage is that it converts hazardous waste (EoL Li-ion batteries) into a saleable commodity that can be shipped without Basel notification. Next to high investment costs, disadvantages are linked to the loss of some embedded materials (e.g. aluminium, graphite) and the operating conditions (high temperature process involving elementary oxygen) requiring well-trained personnel and effective health and safety precautions.

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