Handbook on the Re-use of End-of-Life Lithium-Ion Batteries from E-Waste (WEEE) within the Ghanaian Context

On behalf of the Environmentally Sound Disposal and Recycling of Electronic Waste Programme (E-Waste Programme)

KHACHATUR TORCHYAN, XAVIER SCHUSTER, NOVEMBER 2022

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GIZ Country Office Accra
7 Volta Street | Airport Residential Area
P.O. Box KIA 9698
Accra | Ghana
F +233 302 760 448
E giz-ghana@giz.de
I www.giz.de/ghana
I www.giz.de

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Authors:
Khachatur Torchyan (InnoE), Kuppenheim, Germany
Xavier Schuster (InnoE), Kuppenheim, Germany

Editor:
Xavier Schuster (InnoE), Kuppenheim, Germany

Design/layout, etc.:
Khachatur Torchyan, Kuppenheim, Germany

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Division 203 West Africa II
Contact person at the ministry: Dr. Friederike Fuhlrott
Bonn

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List of Abbreviations

BMS	Battery Management System
BP	Battery pack
DIY	Do-it-yourself
EIS	Electrochemical Impedance Spectroscopy
EU	European Union
EV	Electric vehicles
FITS	Fast Impedance Testing and Sorting
GHS	New Ghana Cedi
GIZ	Deutsche Gesellschaft fur Internationale Zusammenarbeit GmbH
LFP	Lithium-iron-phosphate
Li-ion	Lithium-ion
MESTI	Ministry of Environment, Science, Technology and Innovation
ML	Machine Learning
PCB	Printed Circuit Board
PPE	Personal protective equipment
SoH	State of Health
SOP	Standard Operating Procedures
SRI	Sustainable Recycling Industries
UNEP	United Nation Environmental Program

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1. Overview of e-waste Li-ion batteries in Ghana

The amount of e-waste in Ghana is increasing at an alarming rate. In 2019 only, for instance, the country generated 53,000 tons of e-waste (Forti et al, 2020). The composition of this waste is very varied and consists of any kind of electronic devices, an important quantity of which contains used or end-of-life Li-ion batteries. These batteries are found in a variety of applications, including laptops, cell phones, and power tools. For this reason, each year, hundreds of tons of Li-ion batteries are sent to landfill sites in Ghana, mixed with or embedded inside of consumer electronics.

If we focus on recycling and disposal of waste coming from electronic appliances, Ghana experiences the coexistence of formal and informal streams. Considering 171,000 tons of e-waste generated in 2011, for instance, only 0.2% were processed by formal e-waste recyclers (UNEP). The remaining 99.8%, instead, were processed via a non-regulated and non-formalized network of unlicensed players such as collectors, intermediaries, scrap dealers and dismantlers. These players mainly specialize in manually disassembling post-consumer electronics and in their trade. This lack of dominance of a formalized recycling industry leads to several challenges related not only to estimation of volumes and to a fair trade and competition but also to health risk incurred by the industry operators.

The constant increase of volumes of e-waste and number of batteries to dismantle in Ghana is in line with global trends, where the lithium battery demand is forecast to grow 5 times from 2022 to 2030 (Statista, 2021). Worldwide, this growth in demand is mainly driven by the emerging market of electric vehicles, closely followed by consumer electronics applications and energy storage systems (Grand View Research, 2021). These trends and drives corroborate the need for evaluating and implementing safe and viable end-of-life lithium batteries processing procedures and standards.

Several studies have revealed that the Basel Convention is being violated, as the e-waste collected in developed countries for recycling is being illegally processed or disposed of in the developing world, including Ghana. E-waste frequently enters the country as wrongly declared second-hand goods or working devices for donation and may end up as e-waste. Odeyingbo et al. (2017) show that although the Basel Convention bans the import of e-waste, legal compliance is still a serious problem in exporting and importing countries. If we also consider that approximately 30–40% of imported second-hand electronics do not function (Schluep et al., 2012), it becomes clear that addressing the Ghanaian challenges provides a great boost to the actuation of the principles of a circular economy at a global scale.

In the Ghanaian context, and for the sake of this handbook, we exclude the batteries coming from the e-waste of mobility sector. As per today, indeed, e-waste systems and schemes in Ghana do not yet cover any kind of batteries or electrical components of vehicles (Forti et al, 2020). Therefore, the handbook focuses on the re-use of the end-of-life Li-ion batteries coming from the e-waste, such as the handheld power tools, mobile phones, laptops, power banks, telecommunication equipment, solar energy storage, etc.

2. Categorization of e-waste Li-ion batteries

2.1. Categorization by cell layout

2.1.1. Single-cell batteries

Batteries that consist of only one single cell. These types of batteries are usually found in mobile phones and small handheld devices such as flashlights, trimmers, vapors and etc.

2.1.2. Multi-cell batteries

Batteries that consist of more than one cell connected in series and parallel to reach the necessary voltage and current levels. These types of batteries are usually found in notebooks, vacuum cleaners, power tools, power banks and etc.

2.2. Categorization by Li-ion cell format

2.2.1. Cylindrical cells

Cylindrical cells are of interest since they always have the same standardized dimensions and are cross-platform compatible, one can use the same cell from a power tool battery pack and put in a different application like a vapor for example.
Cylindrical cells:

- Come in few commonly used shapes: 14500, 18650, 21700, 26650
- They look the same: A cylinder with negative and positive tabs on the bottom and on the top
- No special connector needed to use the cell in another application

Figure 2-1: Types of cylindrical cells

Source: https://image.made-in-china.com/43f34j00FKZTsoUGnygu/Rechargeable-18650-Cylindrical-Lithium-Ion-Battery.webp

Cylindrical cells were first used in laptops, which contained between three and nine cells.
Cylindrical cells are widely used in:

- power tools,
- toys,
- lamps,
- power banks,
- medical instruments,
- handheld military, consumer, commercial, and industrial devices
- portable mobile energy systems,
- EVs, E-Bikes & E-Scooters.

Figure 2-2: Power-tool, e-scooter and old laptop battery pack with Li-ion cells

Source: https://i.ytimg.com/vi/ukKuCGG38n8/maxresdefault.jpg
https://www.smartpropel.com/wp-content/uploads/2021/06/36V-7.8Ah-4.jpg
https://www.notebooksbilliger.de/lenovo+thinkpad+battery+70+9+zellen

2.2.2. Pouch cells

Pouch cells are widespread in smartphones, drones, laptops, wearable devices, etc.

Figure 2-3: iPhone pouch cell

Source: https://guide-images.cdn.ifixit.com/igi/JWCS3PHnITsAmBVa.full

Pouch cells

- come in different shapes and sizes,
- the placement of negative and positive electrodes can vary from cell to cell,
- the connector used can differ from one application to another.

These cells can only be used in the same application as they will not physically fit into another application. Currently, there are no procedures for reusing the pouch cells except to re-use them in the same application if the battery still has enough capacity. The only way to extract some value from the pouch cells is the recycling and extraction of electrode material, which is a highly toxic and hazardous process and should only be performed in specialized recycling centers following local and international regulations.

2.2.3. Prismatic cells

The prismatic cells are larger size than the cylindrical or the pouch cells and are mainly used in the EV applications and are of LFP chemistry. Thus, they will not be further discussed in the handbook.

Figure 2-4: Prismatic cells

Source: https://www.flashbattery.tech/wp-content/uploads/2020/01/celle-prismatiche.png

Thus, the handbook will focus only on the e-waste battery packs which consists of cylindrical cells.

3. End-of-Life management of Li-ion batteries

Following the three Rs of sustainability: Reduce, Re-use, Recycle, the Li-ion batteries that reached their end-of-life should be either re-used or recycled.

3.1. Re-use of Li-ion batteries

Reusing the Li-ion batteries is also reducing the amount of waste generated and also reduces the amount of newly manufactured batteries, which in turn reduces the energy used and the carbon footprint.

The Li-ion batteries can be repaired and re-used for the same application or can be dismantled to cell level and re-used in the creation of a second-life battery for another application, for example energy storage system for solar systems.

The re-use is preferable to recycling as the batteries do not need to be re-processed before they can be used again, which saves money, energy and reduces the environmental impact.

3.2. Recycling of Li-ion batteries

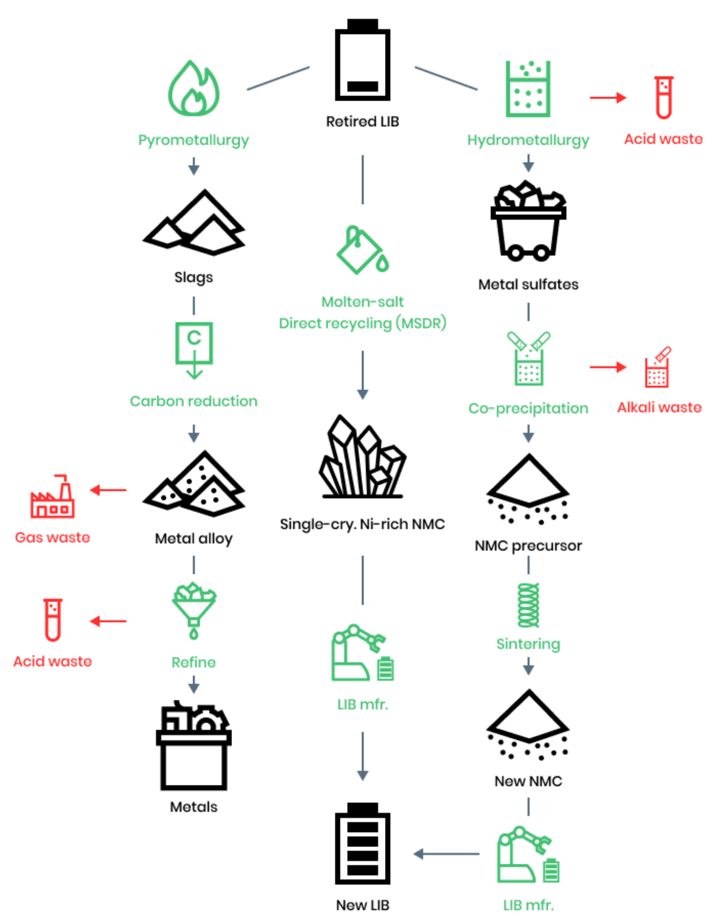
All the materials used in Li-ion batteries have value and can be recovered during the recycling process and later be used in the manufacturing of new Li-ion cells and batteries. However, the recycling of the battery packs is an energy intensive and hazardous process and for some types of Li-ion batteries, such as LFP batteries, the recycling comes with net costs.

Moreover, these processes require additional steps that include disassembly, crushing, screening, magnetic separation, washing, heating treatment, etc. Chemical processes can be divided into pyrometallurgical and hydrometallurgical processes, which usually involve leaching, separation, extraction and chemical/electrochemical precipitation, as presented in the Figure 3-1. Both of these processes are energy intensive and hazardous.

Pyrometallurgy uses heating to convert metal oxides used in battery materials to metals or metal compounds. In smelting, the battery materials are heated under vacuum or inert atmosphere to convert the metal oxides to a mixed metal alloy containing cobalt, nickel, copper, iron, and slag containing lithium and aluminium. Pyrometallurgical methods require simpler pre-treatment methods (most often shredding or crushing) to prepare batteries for recycling and require fewer different methods to recycle LIB of differing compositions, shapes, and sizes. Lithium is recyclable by some pyrometallurgical methods, but the methods are most effective for particularly valuable metals such as cobalt. The by-products of this process are hazardous gases and acid waste.

Hydrometallurgical processes are mainly water-based solutions to extract and separate metals from Li-ion batteries. The pre-treated battery materials are most often extracted with sulfuric acid and hydrogen peroxide, although hydrochloric acid, nitric acid, and organic acids including citric and oxalic acids are commonly used. Once metals have been extracted into solution, they are precipitated selectively as salts using pH variation or extracted using organic solvents containing extractants such as dialkyl phosphates or phosphinates. The by-products of this process are hazardous alkali and acid waste.

Figure 3-1: Overview of Li-ion battery recycling process



Source: InnoE GmbH

Direct methods, where the cathode material is removed for re-use or reconditioning, require disassembly of Li-ion batteries to yield useful battery materials, while methods to renovate used batteries into new ones are also likely to require battery disassembly, since many of the failure mechanisms for Li-ion batteries require replacement of battery components. Re-use of Li-ion batteries in stationary applications will require battery classification and the determination of charge state and capacity.

The recycling can only be done in specially designed recycling centers with proper equipment and following the health and safety standards and regulations.

Thus, this handbook will only focus on the re-use of Li-ion batteries.

4. Re-use of e-waste Li-ion batteries

This section defines the criteria for re-use and gives detailed explanation of the necessary steps for the re-use of e-waste Li-ion batteries.

4.1. Re-use criteria and applications

This subsection defines different second-life applications for the used Li-ion batteries and their corresponding criteria and specifications.

Due to the differences in the shape and type of contactors the Li-ion batteries can be directly re-used only in the same equipment from which they were extracted.

The batteries that cannot be directly re-used need to be dismantled to cell level and the cells might be used in the following applications:

- Energy storage system
- Power bank
- Less power-consuming equipment
- Refurbished battery packs for the same application

4.2. Li-ion battery re-use preparation steps

This subsection presents the steps necessary to select and prepare the Li-ion batteries for re-use.

In every step of preparation appropriate safety equipment needs to be worn.

4.2.1. Safety requirements

Since the Li-ion batteries are hazardous goods, they need to be treated accordingly and safely during the whole process of operation.

Safety standards like OHSAS 18001 or ISO 45001 should be implemented at the workplace and standard operational procedures (SOP) for working with Li-ion batteries and for emergency situations should be defined.

4.2.1.1. General safety requirements

- *Stay alert*: The more awake a worker is, the less likely he or she is to get hurt. If you are unsure how to operate equipment or perform a task, ask your supervisor. Don't guess and muddle through. Make sure you know in advance the correct, safe way to do it.
- *Wear the right protective clothes and equipment*: Personal protective equipment (PPE) such as gloves, shoes and glasses, should be worn all the time. In case of emergencies, special protective equipment should be worn.
- *Use the right tool*s: If you need a hammer, get a hammer, don't use whatever is handier.
- *Be serious*: Showing off and pranks can be dangerous, especially when dealing with dangerous goods such as Li-ion batteries.
- *Be tidy*: Keep your workplace clean and tidy. Always put away tools when they are not in use. A mess on the workbench can cause accidental short-circuits. Keep the floors clean, pick up scraps and wipe up spills. A slip or trip can be fatal.
- *Report the accidents*: Always report the accidents, even the minor ones.
- *Get First Aid immediately*: Get first aid immediately even if the injury is a minor one. Neglect of an injury may lead to serious infection, weeks of lost time, and possibly permanent injury, especially when dealing with Lithium electrolyte.
- *Always follow the SOPs*: Whatever you are doing, if you are not doing it safely, you are not doing it right
- *Get appropriate training*: Make sure you know in advance the correct way to use all the equipment necessary for your work, the PPE and the fire extinguishers.
- *Repeating leads to perfection:* Make regular safety trainings and drills to keep your workers alert

4.2.1.2. Safety procedures

Below are the recommended safety procedures for most common emergency situations that might occur while working with Li-ion batteries and cells

Overheating, Venting and Leaking Cells/Batteries

When a cell's internal temperature and pressure rise faster than the rate at which they can be dissipated, cell overheating will occur. This may be caused by electrical shorting, rapid discharge, overcharging, manufacturer defects, poor design, or mechanical damage, among many other causes. The overheating of a given cell may produce enough heat to cause adjacent cells to overheat in response. If the cell does not return to room temperature it may vent and catch fire, or explode. Sounds like "clicks" and "puffs" may indicate a preliminary vent release. Depending on the cell type and manufacturer, the critical temperature ranges around 120-300 °C (250-570 °F) (see manufacturer manual for details on the battery you are using). Follow this emergency procedure if you have overheating, venting or leaking cells.

Procedure

- If you notice hot cells/batteries, disconnect the charger and remove any external short circuit if present.
- If a cell/battery is venting or smoking,

  - evacuate all personnel from the area,
  - put on fire-proof gloves and a gas mask,
  - put the cell/battery inside a metal or hard plastic barrel filled with 3% salt water solution,
  - label the barrel as hazardous waste and put outside,
  - after 48 hours dispose the cell/battery and the contaminated water following the local regulations.

- If leaking material is present, do not touch it.
- Do not approach the cell until it reaches room temperature. The cell temperature can be checked using a remote device (i.e. infrared thermometer).
- If a remote device is not available, do not handle the cell for a period of at least 24 hours.
- As soon as the cell reaches room temperature, label it as hazardous waste and dispose it following the local regulations.

Exploded Cell

Like a vented cell, an exploded cell is the result of an overheated or mechanically damaged cell. After the explosion of a lithium-ion battery, the room could fill quickly with dense white smoke that could cause severe irritation to the respiratory tract, eyes and skin. All precautions must be taken to limit exposure to these fumes.

Procedure

- If a cell has exploded, evacuate all personnel from the area. The area should be secured to ensure that no unnecessary personnel enter.
- If a ventilation system is in place and it is safe to, turn it on, initiate ventilation and continue until the cell is removed from the area and the pungent odour is no longer detectable.
- Remove the damaged cell/battery, place the battery/cell in a container of sand or another chemically-inert cushioning material, such as vermiculite, label it as hazardous waste and dispose it following the local regulations.

Lithium-ion Battery Fires

Li-ion fires may occur as a result of thermal runaway, shorting and other conditions that result in increased temperatures. Once the battery begins to vent flammable vapours, it may quite easily catch fire. Trained fire extinguisher users should attempt to extinguish early stage (incipient) fires only if it is possible to do so safely. Portable fire extinguishers that can be used include ABC (dry powder), carbon dioxide (CO2) and foam (noncombustible). Smothering the fire with sand or sodium bicarbonate may also be effective. After extinguishing the fire water should be used to prevent the affected battery from reigniting and adjacent batteries from overheating.

Procedure for a small scale fire

A typical example is a small wastebasket fire.

- All personnel from the area should be evacuated.

- Activate the nearest fire alarm pull station.
- If you are trained in fire extinguishers and knowledgeable of the type of battery in use, take the closest CO2 or ABC extinguisher.
- Make sure you are positioned between the fire and the nearest exit before attempting to extinguish the fire.
- If the use a portable fire extinguisher has little effect on extinguishing the fire, exit immediately. Do not initiate a second attempt.
- If you are able to put out the flames, pour water over the battery to cool it down if this will not create an electrical hazard. You might need 1 to 5 or more liters of water depending on the size of the battery in use.
- By-products of combustion may be toxic when inhaled. In the event of heavy smoke, exit the area immediately. Ensure others have left the area and close doors behind you as you leave.
- After the situation is under control, place the battery/cell in a container of sand or another chemically-inert cushioning material, such as vermiculite, label it as hazardous waste and dispose it following the local regulations.

Large scale fire

In the event of a “larger” fire that has been active for a time, and/or those involving furnishings, interior finishes, and structural building components, evacuate the area.

- Activate the nearest fire alarm pull station. Do not attempt to extinguish the fire by using a portable fire extinguisher.
- Call the emergency from a safe location.
- After the situation is under control ensure the proper clean-up and waste management following the local regulations.

First Aid Procedures in Case of Contact with Electrolyte

- While the electrolyte composition will vary depending on the type of the battery cell, the general first aid procedures are the same for an exposure to the electrolyte.
- *Eyes*: Immediately flush eyes with a direct stream of water for at least 15 minutes while forcibly holding eyelids apart to ensure complete irrigation of all eye and lid tissue. Get medical attention, if necessary.
- Remove contaminated garments.
- *Skin*: Flush with cool water or get under a shower. Remove contaminated garments. Continue to flush for at least 15 minutes. Get medical attention, if necessary.
- *Inhalation*: Move to fresh air. Monitor airway breathing; if breathing is difficult, have trained person to administer oxygen. If respiration stops, give proper first aid and/or proper CPR procedures only if CPR-trained. GET MEDICAL ATTENTION IMMEDIATELY.
- For significant exposures to the electrolyte, get immediate medical attention.

Figure 4-1: Personal protective equipment

Source: hsebazr.com

Figure 4-2: Emergency equipment

Source: Ytimg.com / smartpropel.com / notebooksbilliger.com

4.2.2. Visual inspection

Visual inspection of the batteries for mechanical and chemical damages.

The first step in the battery re-use preparation is the visual inspection. The battery pack should be visually checked for damages. The battery packs that have been subject to chemical or fire damage are not safe to operate with and should not be processed further. They should be stored in containers with sand and be sent to recycling centers.

Figure 4-3: Damaged cylindrical cell battery

Source: Pottsmerc.com

- The batteries with mechanical damage can still be further processed for cell extraction and upcycling.
- The batteries without visible damage should be further assessed for reusability.
- Pouch cell batteries with any sign of swelling, fire or chemical damage should be sent to recycling centers.

Figure 4-4: Swollen pouch cell battery

Source: PCmag.com

4.2.3. Electrical inspection

After the visual inspection is done, the next step is the electrical inspection of battery packs. The electrical inspection includes checking the open circuit voltage and the integrity of the connector.

To perform the electrical inspection the following equipment is needed:

- Multimeter

Figure 4-5: Multimeter

Source: Uni-trend.com

- Pliers set

Figure 4-6: Pliers set

Source: THDstatic.com

- Insulated screwdrivers set

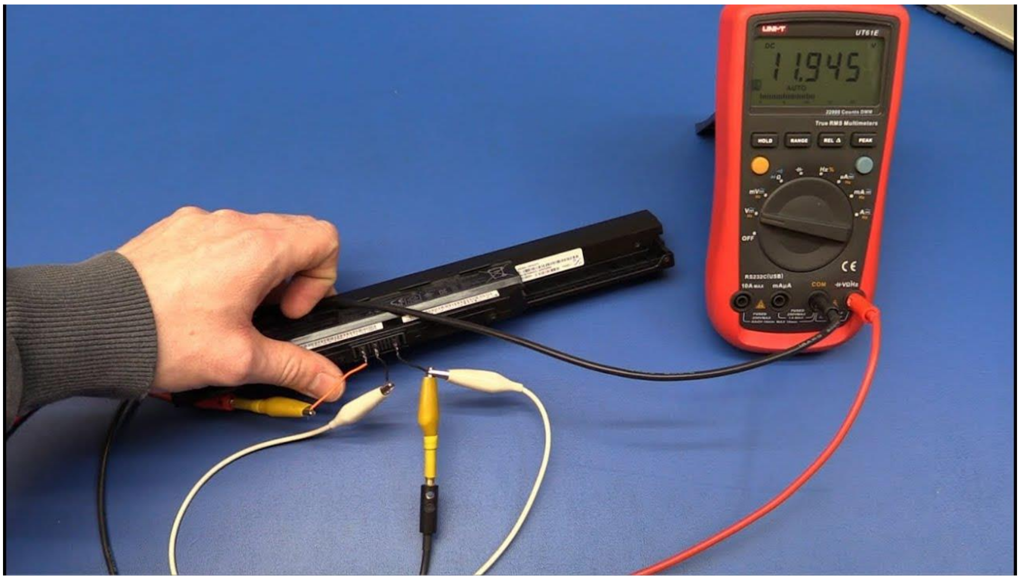
Figure 4-7: Insulated screwdrivers set

Source: Sydneytools.com

Electrical inspection includes:

- Integrity check of the connector
  - Use a multimeter and hand tools to check the integrity of the connector
    - If the connector is not damaged, the inspection should continue
    - If the connector is damaged
      - Fix the connector and continue the inspection
- Open circuit voltage check
  - Use a multimeter to check the voltage levels
    - If the battery is in deep discharge state, the battery should be charged with low current
    - If the voltage is 0V, the battery should be sent to cell extraction
    - If the voltage is within the nominal operating voltage of the battery pack, the battery pack should be diagnosed further to assess the health of the pack

Figure 4-8: Electrical Inspection of a laptop battery



Source: ytimg.com

4.2.4. Diagnostics

After the mechanical and electrical inspections of the battery packs are done, the battery packs that were sorted as re-usable should be further diagnosed to identify their actual re-usability.

To diagnose the battery packs, in addition to the equipment described in the previous section, the following equipment is needed:

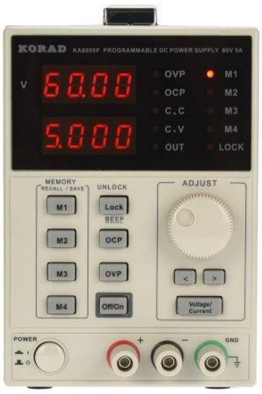
- Programmable electronic load

Figure 4-9: Programmable electronic load

Source: static.eleshop.nl

- Programmable power supply

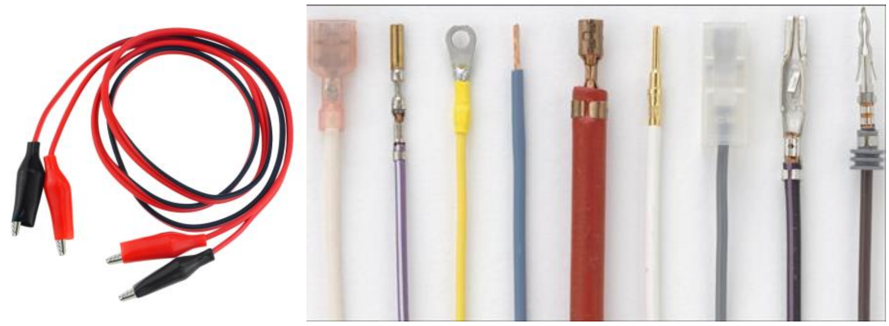
Figure 4-10: Programmable power supply



Source: static.eleshop.nl

- Cables

Figure 4-11: Cables



Source: InnoE GmbH

To diagnose a battery pack, the following steps need to be performed:

a) Discharge the battery using an electronic load in constant current mode at 1C or 0.5C discharge current

b) Perform a constant current constant voltage charging of the battery using a programmable power supply at 1C or 0.5C

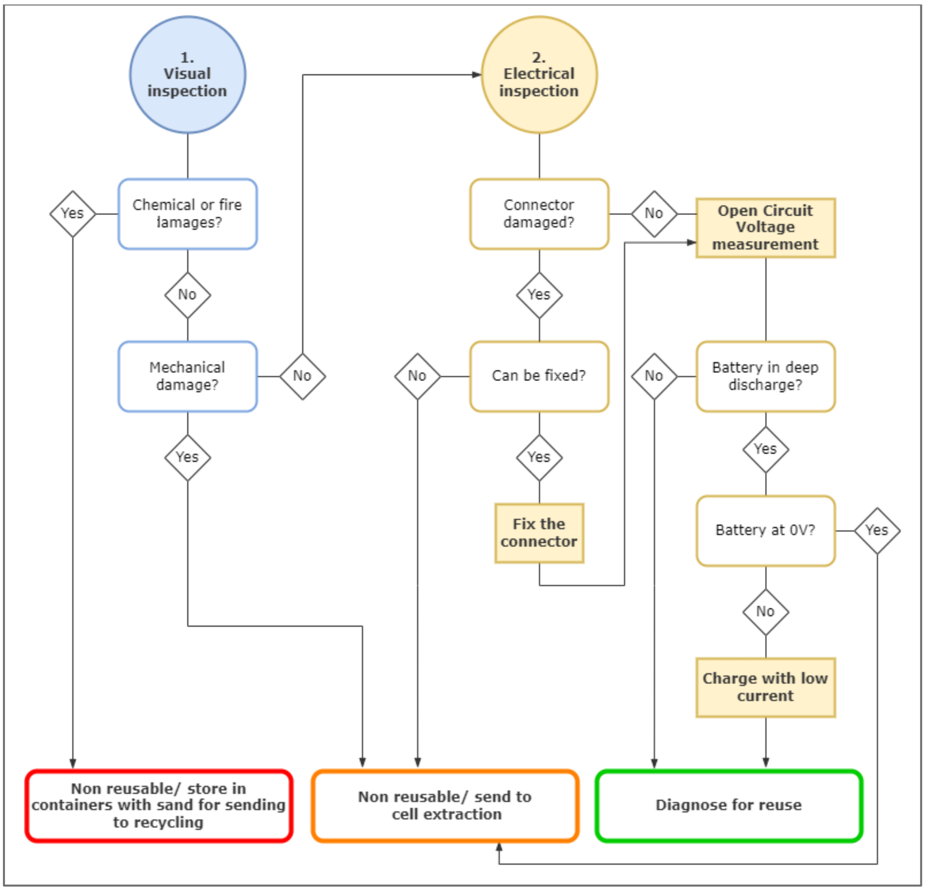
c) Discharge the battery with 1C or 0.5C and record how many Ah has been extracted from a pack

If the state-of-health (SOH) of a battery pack is more than 70%, the battery pack can still be re-used in the same application. If not, the cells from the battery should be extracted and diagnosed to find the cells that can be re-used in other applications.

4.2.5. Sorting summary of the Li-ion batteries

Based on the acquired results, the batteries will be sorted into different categories as presented in the diagram below:

Figure 4-12: Sorting diagram of Li-ion batteries



Source: InnoE GmbH

5. Conditioning of non-re-usable e-waste Li-ion batteries

This section presents the needed steps for preparing the non-re-usable Li-ion batteries for further processing.

The non-reusable e-waste Li-ion batteries which are damaged by fire or chemical leakage should be properly stored in containers with sand and be sent to recycling. The other non-reusable batteries that consist of cylindrical Li-ion cells should be further prepared for cell extraction and analysis of the cells. The research shows that around 85% of the cells inside non-reusable batteries from the e-mobility sector in EU are still good to be used. Even though this number can change when changing from one sector to another, the extraction of the cells from e-waste Li-ion batteries is still feasible.

5.1. Processing options

This subsection presents the available processing options for non-re-usable Li-ion batteries and their requirements.

5.1.1. Option 1: Storage for further recycling

The battery packs that cannot be re-used should be isolated from short-circuits and stored in containers with sand or vermiculite according to UN38.3 standard for transporting Li-ion batteries.

Afterwards, the containers should be labelled and sent to the recycler.

Figure 5-1: Container with Vermiculite and UN38.3 labeling

Source: InnoE GmbH

5.1.2. Option 2: Cell extraction and upcycling of cells

Cell extraction and upcycling is the next option for extracting value from non-re-usable Li-ion battery packs. In this section, the handbook describes the steps necessary to upcycle.

5.1.2.1. Safety measures

Working with Li-ion batteries and especially extracting the cells from the batteries is a dangerous process. In case of improper handling the cells and the batteries can catch fire and injure the workers.

Same safety requirements and procedures as in Section 2 should be followed when extracting cells from the battery packs. Moreover, cell extraction standard operational procedures should be developed for each battery model, similar to the one presented in the Appendix A1.

5.1.2.2. Tools needed

Usage of appropriate tools ensures the safety of the work. In addition to the tools described in Section 2, the following tools are needed for safe extraction of the cells from battery packs:

- Hammer

Figure 5-2: Hammer

STANLEY WOOD HAN  DLE NAIL HAMMER – Rakan

Source: rakanjayahardware.com

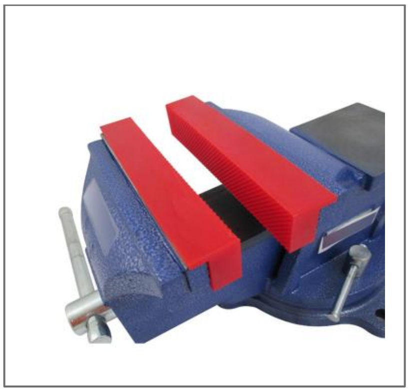
- Plastic case opening tools

Figure 5-3: Plastic tools for case opening

Source: parts4laptops.com

- Vise with plastic jaws

Figure 5-4: Vise with plastic jaws



Source: alibaba.com

Where applicable, plastic tools should be used to avoid short-circuits.

5.1.2.3. Cell extraction and diagnostics

As mentioned previously, proper steps and tools need to be used to ensure safe extraction of the cells.

To extract the cells from the battery packs the following steps need to be performed:

a) Discharging the battery to a safe operating voltage.
With the help of a programmable electronic load the battery should be discharged to a safe operating level. The exact level of discharge depends on the individual battery model.

b) Manual extraction of cells from batteries.
To perform the manual extraction of cells from batteries the following steps need to be performed:

- Opening of the battery pack casing
- Removal of the cell pack from the casing

- Removal of the battery management system (BMS)
- Removal of the busbars
- Singularization of the cells

In the process of extraction of the cells the following components can be collected, stored and used for the refurbishment of batteries:

- Case
- Cell holders/spacers
- BMS PCBs
- Copper wires
- Connectors

In the process of extraction of the cells the following components should be collected, stored and sent to recycling if no re-use is planned:

- Plastic casing and components
- Aluminum components (casing)
- Protection Circuit Boards (PCBs)
- Copper wires
- Nickel busbars

5.1.2.4. Diagnostics and sorting of each cell

After the cells are singularized, they need to be diagnosed and sorted for future use in the second-life application or for selling.

Diagnostics of the cells can be done using different techniques, with different accuracy, diagnostics time, added value and cost.

a) *DIY grade diagnostics and sorting*

Using handheld 1kHz impedance measurement devices and battery charger-testers that can be easily purchased in DIY shops or websites like ebay, aliexpress or amazon.

This method is cheap and can be used if high accuracy is not important. The cells diagnosed with this method will have less value.

- Advantage:
    - Cheap
    - Gives a general idea on the state of the cell
- Disadvantage:
    - Not accurate

    - Not enough to characterize the performance of the cell

b) *Laboratory level diagnostics and sorting*

Using off-the-shelf high precision EIS (Electrochemical Impedance Spectroscopy) measurement device that does sequential impedance measurements at different frequencies and cell cyclers that measure the capacity of the cells with high accuracy.

- Advantage:
    - Accurate
    - State-of-the-art
- Disadvantage:
    - Expensive, in the range of 100k EUR
    - Is slow
        - Complete EIS spectra measurement of one cell can take around 2-20 minutes depending on the hardware chosen
        - Capacity measurements of one batch (80-96) of cells can take up to 6 hours
    - Manual sorting of the cells needed

c) *Fast diagnostics and sorting*

Using fast impedance testing and sorting (FITS) equipment that does simultaneous EIS measurements and uses Li-ion cell models and special ML algorithms for analysing the health of the cell and calculating the capacity of the cell with accuracy of >98%

- Advantage:
    - Accurate
    - Fast, less than 5 seconds
    - State-of-the-art
    - Automatic sorting of the cells
    - Configurable sorting parameters
- Disadvantage:
    - Expensive, 40-60k EUR

5.1.2.5. Sorting of the cells

Sorting of the cells should be done based on the measured capacity and impedance values according to the second-life application needs.

Below is a table with common sorting requirements depending on the second-life applications

Table 5-1: Sorting requirements of the cells based on the second-life application

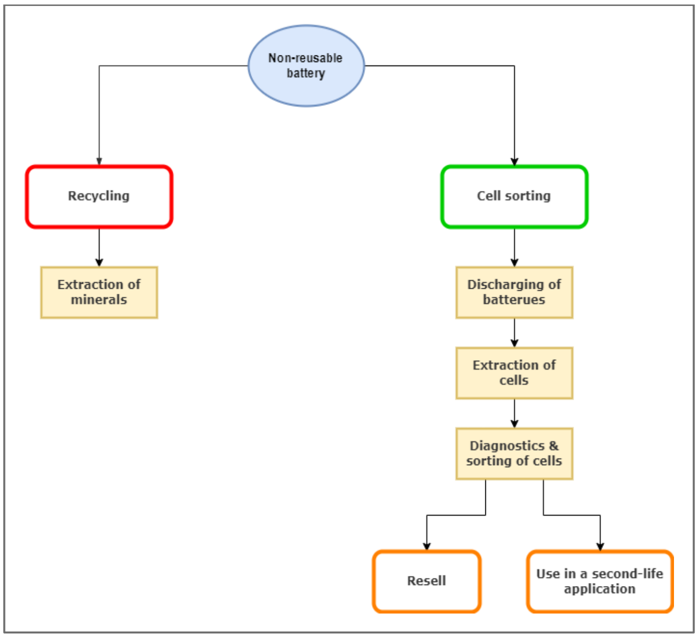
Second-life application	SoH requirement	Impedance
Second-life battery pack for the same application	>90%, <5% variation for multicell batteries	Variation within 5mOhms or +- 5% whichever is smaller
Energy storage system	>70%, < 5% variation within battery	Variation within 5 mOhms or +- 5% whichever is smaller
Power bank	> 60%, < 5% variation within battery	Variation within 5mOhms or +- 5% whichever is smaller
Second-life battery pack for less power-consuming equipment	>50%, <5% variation for multicell batteries	Not important for single cell batteries, Variation within 5mOhms or +-5% for multicell batteries whichever is smaller

Source: InnoE GmbH

5.2. Processing summary of non-reusable Li-ion batteries

This subsection presents a summary diagram of the further processing options of non-reusable Li-ion batteries.

Figure 5-5: Processing diagram of non-reusable Li-ion batteries



Source: InnoE GmbH

6. Business case implementation

This section presents guidelines and describes the framework needed for the implementation of a business case for the re-use of the e-waste Li-ion batteries in Ghana.

6.1. Guidelines

This subsection provides guidelines for implementing the proposed re-use approaches as business cases. Four business cases will be discussed in the next sections of the handbook.

For the analysis of the revenues and expenses the following assumptions are made that are common for all the business cases:

Table 6-1: Common assumptions for the business cases calculation

Item	Amount
Number of cells in a battery pack	8
Percentage of good cells in a pack	60%
Yearly salary of a worker	1,400 EUR
Yearly salary of a foreman	3,120 EUR
Price of electricity per kWh	0.1 EUR
Number of working days per year	255
Number of hours per shift	8
Price of a collected battery	0.05 EUR/kg
Weight of a battery	1.5 kg
Depreciation of equipment costs	5 years

Source: GiZ

6.1.1. Business case 1: Refurbishment of the Li-ion batteries

This business case is based on the Li-ion battery re-use steps presented in Section 4 and implies refurbishment of the batteries and their further resell.

To implement the business case a localized battery repairs facility nearby the battery collection point has to be established.

As a basis for the calculation of the business case, the daily throughput of 20 battery packs is taken.

The input parameters for the business case are presented in the table below.

Table 6-2: Input data for the business case 1 (+/- 5000 battery packs per year)

Item	Amount
Daily throughput of battery packs	20
Percentage of good reusable battery packs	30%

Item	Amount
Price per refurbished battery pack	20 EUR

Source: InnoE GmbH

To guarantee the mentioned throughput, the facility needs to be equipped with:

- 10 programmable loads, with a throughput of 2 battery packs per day each, for discharging the batteries and ensuring the safety of the process;
- 10 programmable power supplies, with a throughput of 2 battery packs per day each, for charging and testing the batteries;
- 3 Hand tool sets (screwdrivers, pliers, plastic tools, wire cutters, hammers, vice);
- 3 multimeters;
- 3 Protective equipment (safety work gloves, safety goggles, safety shoes, fireproof gloves, barrel with water).

Total equipment cost for this solution will be 6,500 EUR.

To ensure smooth operation of the facility, one worker needs to take care of preparation of incoming batteries for repairs and diagnostics, one more worker should take care of charging, discharging and testing the batteries, one more person will work on the refurbishment. To coordinate the work process a foreman will be required. Thus, to implement the business case 3 workers and a foreman will be needed.

The facility needs to have electricity connection and be big enough to accommodate all the equipment and the workers.

The summary of the expected money flows is presented in the table below

Table 6-3: Summary of expected money flows

Item	Amount
Amortization / year	1,300 EUR
Fixed costs (Facility)	5,000 EUR
Labour cost	7,320 EUR
Energy	1,428 EUR
Raw material	383 EUR
Expected revenue	30,600 EUR
Expected profit	15,170 EUR

Source: InnoE GmbH

6.1.2. Business case 2a: Low accuracy sorting of the cells

This business case is based on the extraction, diagnostics and sorting of the non-reusable Li-ion batteries presented in the Section 5: *DIY grade diagnostics and sorting*.

To implement the business case a localized cell sorting facility nearby the battery collection point has to be established.

As a basis for the calculation of the business case, the daily throughput of 20 battery packs is taken.

The input parameters for the business case are presented in the table below.

Table 6-4: Input data for the business case 2a (+/- 5000 battery packs per year)

Item	Amount
Daily throughput of battery packs	20
Percentage of good reusable cells within a pack	60%
Price per second-life cell	1.5 EUR

Source: InnoE GmbH

The low price of 1.5 EUR/cell is based on the fact that not diagnosed cells cost around 0.3 to 0.7 EUR depending on their nominal capacity.

Taking into account that one person is assumed to be able to extract the cells from a battery pack in 30 minutes, one person can extract cells from 16 batteries in a day. Considering also the fact that the battery packs need to be discharged and the cells need to be tested afterwards, three workers will be needed to perform the extraction and sorting of the cells and one foreman will be needed to operate the facility.

To guarantee the mentioned throughput, the facility needs to be equipped with:

- 10 programmable loads, with a throughput of 2 batteries per day each, for discharging the batteries and ensuring the safety of the process;
- 20 cell charger/testers, with 4 cell slots and 8 cell per day throughput each;
- 4 handheld AC impedance measurement tools;
- 3 hand tool sets (screwdrivers, pliers, plastic tools, wire cutters, hammers, vice);
- 3 multimeters
- Protective equipment for 3 workers (safety work gloves, safety goggles, safety shoes, fireproof gloves, barrel with water).

Total equipment cost for this solution will be 5,800 EUR.

The outcome of this business case will be manually sorted cells of low value, as the equipment used is not high accuracy equipment and can be bought from DIY stores and websites.

The facility needs to have electricity connection and be big enough to accommodate all the equipment and the workers.

The summary of the expected money flows is presented in the table below

Table 6-5: Summary of expected money flows per year for case 2a

Item	Amount
Amortization / year	1,160 EUR
Fixed costs (Facility)	5,000 EUR
Labour cost	7,320 EUR
Energy	1,020 EUR
Raw material	383 EUR
Expected revenue	36,720 EUR
Expected profit	21,838 EUR

Source: InnoE GmbH

6.1.3. Business case 2b: High accuracy slow sorting of the cells

This business case is based on the extraction, diagnostics and sorting of the non-reusable Li-ion batteries presented in the Section 5: *Laboratory level diagnostics and sorting*.

To implement the business case a localized cell sorting facility nearby the battery collection point has to be established.

Since the initial equipment costs are high in this case, the daily throughput of the EIS measurement device is taken as a basis for the calculation of the business case. The throughput of the machine itself is around 20 seconds per cell – however, taking into account all the manual work that needs to be done, 2 minutes per cell is more realistic. Thus, the throughput will be 240 cells per day or 30 batteries per day.

The input parameters for the business case are presented in the table below.

Table 6-6: Input data for the business case 2b (+/- 7500 battery packs per year)

Item	Amount
Daily throughput of battery packs	30
Percentage of good reusable cells within a pack	60%
Price per second-life cell	3 EUR

Source: InnoE GmbH

Taking into account that one person is assumed to be able to extract the cells from a battery pack in 30 minutes, one person can extract cells from 16 batteries in a day. Thus, two workers will be needed for cell extraction. Considering also the fact that the battery packs need to be discharged and the cells need to be tested afterwards, four workers will be needed in total to perform the extraction and sorting of the cells and one foreman will be needed to operate the facility.

To guarantee the mentioned throughput, the facility needs to be equipped with:

- 15 programmable loads, with a throughput of 2 batteries per day each, for discharging the batteries and ensuring the safety of the process;

- 1 EIS measurement device with frequency sweep;
- 30x 8 channel cyclers for high accuracy capacity measurements of the cells;
- 4x Hand tool sets (screwdrivers, pliers, plastic tools, wire cutters, hammers, vice);
- 4x Protective equipment (safety work gloves, safety goggles, safety shoes, fireproof gloves, barrel with water).

Total equipment cost for this solution will be 75,000 EUR.

The outcome of this business case will be manually sorted cells of high value, as the equipment used for the measurements is laboratory grade.

The facility needs to have electricity connection and be big enough to accommodate all the equipment and the workers. The facility should be bigger than in previous two cases because the size of each 10x 8 channel cyclers is one rack of the size of a server.

The summary of the expected money flows is presented in the table below

Table 6-7: Summary of expected money flows for case 2b

Item	Amount
Amortization / year	15,000 EUR
Fixed costs (Facility)	10,000 EUR
Labour cost	8,720 EUR
Energy	3,998 EUR
Raw material	574 EUR
Expected revenue	110,160 EUR
Expected profit	71,868 EUR

Source: InnoE GmbH

6.1.4. Business case 2c: High accuracy fast sorting of the cells

This business case is based on the extraction, diagnostics and sorting of the non-reusable Li-ion batteries presented in the Section 5: *Fast diagnostics and sorting*.

To implement the business case a localized cell sorting facility nearby the battery collection point has to be established.

Since the initial equipment costs are high in this case, the daily throughput of the fast impedance testing and sorting system (FITS) that does the diagnostics and automatic sorting of the cells is taken as a basis for the calculation of the business case. It is estimated that the throughput of such a system will be 4,800 cells per day or 600 batteries per day on average.

The input parameters for the business case are presented in the table below.

Table 6-8: Input data for the business case 2b (+/- 150000 battery packs per year)

Item	Amount
Daily throughput of battery packs	600
Percentage of good reusable cells within a pack	60%
Price per second-life cell	3 EUR

Source: InnoE GmbH

Taking into account that one person is assumed to be able to extract the cells from a battery pack in 30 minutes, one person can extract cells from 16 batteries in a day. Thus 38 workers will be needed for cell extraction. Taking into account the fact that the battery packs need to be discharged and the cells need to be tested afterwards, 60 workers in total will be needed to perform the extraction and sorting of the cells and 4 foremen will be needed to operate the facility.

To guarantee the mentioned throughput, the facility needs to be equipped with:

- 300 programmable loads, with a throughput of 2 batteries per day, for discharging the batteries and ensuring the safety of the process;
- 1 FITS system;
- 50x hand tool sets (screwdrivers, pliers, plastic tools, wire cutters, hammers, vice);
- 65x protective equipment (safety work gloves, safety goggles, safety shoes, fireproof gloves, barrel with water).

Total investments for this solution will be 151,000 EUR.

The outcome of this business case will be automatically sorted cells of high value, as the equipment used for the measurements is of high accuracy and fast.

The facility needs to have electricity connection and be big enough to accommodate all the equipment and the workers. The facility should be bigger than in previous two cases because the size of each 10x 8 channel cyclers is one rack of the size of a server.

The summary of the expected money flows is presented in the table below

Table 6-9: Summary of expected money flows for case 2c

Item	Amount
Amortization / year	30,400 EUR
Fixed costs (Facility)	20,000 EUR
Labour cost	96,480 EUR
Energy	18,513 EUR
Raw material	11,475 EUR
Expected revenue	2,203,200 EUR
Expected profit	2,026,332 EUR

Source: InnoE GmbH

6.1.5. Business cases 1 and 2: Conclusion

In all the cases of business case 2 the sorted cells can later be used in different applications, such as energy storage systems, power banks or other. The second-life usage of the cells will not be covered in this handbook.

Another additional revenue stream can be the combination of the business cases 1 and 2 where the cells sorted in the different scenarios of business case 2 and the battery components can be directly used in business case 1. Also, in case of no re-use of battery components they can be collected and sent to recycling.

6.2. Framework

To implement the business cases the centralized collection and separation of e-waste batteries in Ghana needs to be implemented on a larger scale. At the same time, to decrease the transportation costs and the risks associated with the transport of Li-ion batteries it is advised that the abovementioned business cases are implemented locally, nearby the battery collection centers, on a smaller scale with the potential to be extended afterwards.

6.2.1. Legal Framework

Since the Li-ion batteries are considered dangerous goods and also might be explosive, to implement the business cases and develop Li-ion battery re-use infrastructure appropriate local legislation on dealing with dangerous goods should be followed.

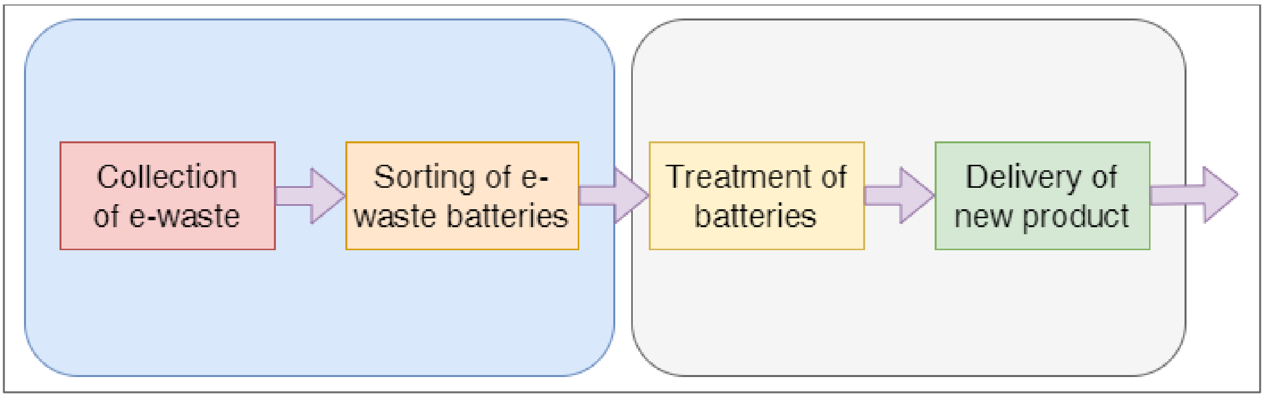
More specifically,

- Regulations 44-59 of Hazardous, Electronic and other Wastes (Classification) Control and Management Regulations, 2016 (LI 2250), should be followed for the clarification of the responsibilities of different actors in the e-waste treatment.
- Regulations 43, 44 and 60 of Minerals and Mining (Explosives) regulations, 2012 (LI 2177) should be followed for obtaining an environmental permit for hazardous wastes, the labelling, marking and packaging of dangerous goods as well as for the requirements of PPE

6.2.2. Infrastructural Framework

To minimize the transportation costs and reduce the risk of accidents during the transportation, the e-waste collection and sorting of e-waste batteries should be performed locally.

Figure 6-1: Infrastructural Framework



Source: InnoE GmbH

7. Appendix

7.1. Sample Standard Operation Procedure for dismantling power tool battery pack

Table 7-1: SOP sample for manual dismantling of a power tool battery

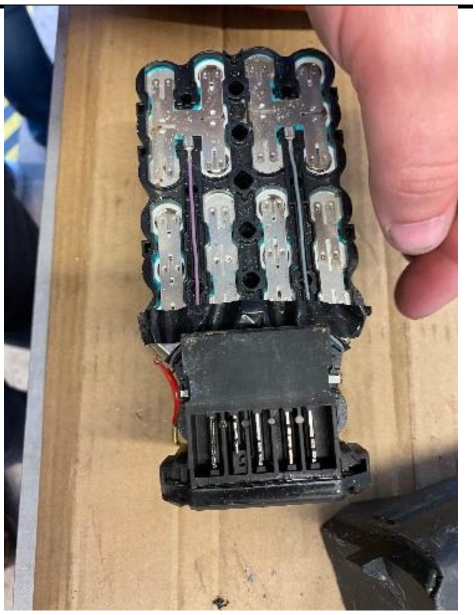
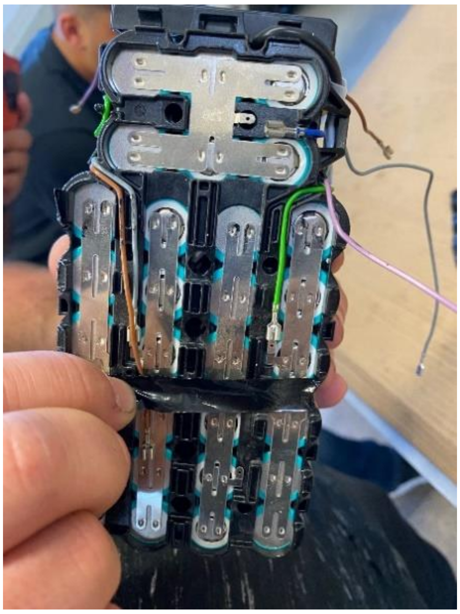
Step	Process step	Picture
1	This battery consists of a case and a cover, both made of plastic. These two components are fixed by 4 screws that can be accessed from the bottom and 2 screws from the top of the battery **Actions taken:** • Unscrew the two covers from the top (2x) • Unscrew the two covers from the bottom (4x) **Removed components** • Screws	

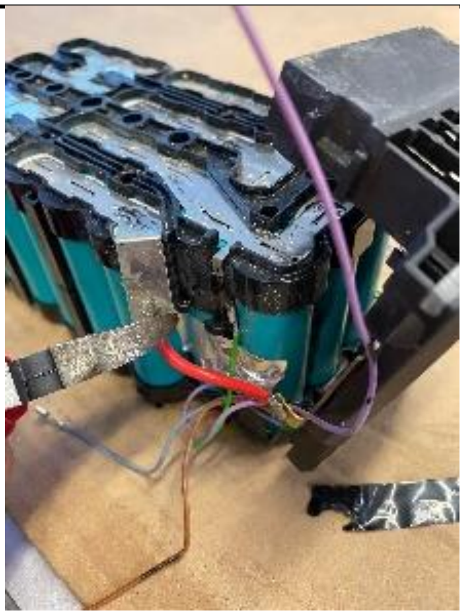
Step	Process step	Picture
		
		

<table>
<tr><th>Step</th><th>Process step</th><th>Picture</th></tr>
<tr><td>2</td><td>The two parts are unscrewed.

<u>Actions taken:</u>
Push on black part (lower part) with a circular movement
<u>Removed components</u>
Black plastic case parts</td><td></td></tr>
<tr><td>3</td><td>The cell pack is fixed with the red part (upper part)

<u>Actions taken:</u>
Push on the black connector on the top of the upper part
<u>Removed components</u>
Red parts</td><td>
</td></tr>
</table>

Step	Process step	Picture
		
4	The cell pack is extracted with the BMS **<u>Actions taken:</u>** • Remove black tape • Remove or cut color wires plug on the cell pack • Cut the red and black cables • Remove the BMS **<u>Removed components</u>** • BMS	

Step	Process step	Picture
		

Source: InnoE GmbH

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