Dealing with the End-of-Life Problem of Electric Vehicle Batteries

Insights and Recommendations for Kenya

Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

On behalf of:

Federal Ministry
for the Environment, Nature Conservation
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of the Federal Republic of Germany

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Project Context

The 'Advancing Transport Climate Strategies' (TraCS) project is funded by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety's, International Climate Initiative. The project aims to support developing countries in systematically assessing GHG emissions from transport, in analysing emission reduction potentials and in optimising the sector's contribution to the mitigation target in countries' NDC. TraCS feeds into other international cooperation projects run by the Government of Germany.

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Exchange rates

Local Currency	EUR	USD	Date
1 KES	0.0078 EUR	0.0092 USD	28.07.2021

List of Acronyms and Abbreviations

AFD	Agence Française de Développement
CO_2	Carbon dioxide
EoL	End of life
EV	Electric vehicle
EU	European Union
GHG	Greenhouse gases
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
LiB	Lithium-ion battery
UN	United Nations
USA	United States of America

1. Introduction

The transformation of the transport sector from reliance on fossil fuel combustion towards electric mobility (e-mobility) powered by renewable energy is pivotal when striving to mitigate greenhouse gas emissions in the sector. In Kenya, the implementation of electric mobility could mitigate emissions by about 0.6 MtCO2e in comparison with the Business as Usual scenario in 2030 (GIZ 2018: 16). Aside from reducing transport emissions electric mobility also causes considerably less air and noise pollution and reduces dependency on petroleum imports. Hence, it offers a pathway towards a more sustainable mobility option overall.

For Kenya, electric mobility is particularly promising for three reasons. Firstly, the energy mix of the country is dominated already by renewable energy (particularly bioenergy) (IEA 2019) and thus, favourable for low carbon electric mobility. Secondly, EVs would also create a demand for the surplus of energy that is currently being produced in the country (Muchira 2019). And thirdly, the country experiences a motorisation rate that is increasing rapidly due to the rise of income levels paired with a growing population. In the KAM Automotive Sector Profile from 2020 it is stated that "Figures for Kenya's motorization rate differs depending on the source and range between 26 and 40 vehicles per 1,000 persons. This is forecast to increase to 70 in 2030, reflecting vehicle ownership growing faster than Kenya's population" (KAM 2020: 4). Hence, demand for private vehicles will rise further in the future and alignment with global climate targets is only possible when turning to electric vehicles (EV). Accordingly, the global e-mobility market is growing rapidly, and pioneer companies have already started operation in Kenya (IEA 2021:5ff, GIZ & MOTIHUD Kenya 2020: 12).

For successful deployment of electric mobility, one needs to think further. Of course, questions around the start of electric mobility implementation, i.e. around demand and provision of EVs, are relevant. Nonetheless, one also needs to take into account concerns that revolve around the end of an EV's lifecycle - in particular the question what to do with the heart of every EV once it is not usable anymore: the battery.

A comprehensive national system for e-mobility requires to think about batteries after end of use for EVs. In Kenya, second hand vehicles make up 80% of the total fleet (Deloitte 2018: 7). This is relevant for electric mobility and battery life considerations. EV batteries usually last for 8 to 12 years depending on charging and driving behaviour (Zhao et al 2021: 189). This means that the batteries built into the imported second hand vehicles have a relatively short lifespan and will need to be reused or recycled few years after use. Smart reuse and recycling systems need to be put in place as they can help to prolong the life cycle of such used batteries and provide significant business opportunities.

This short paper gives an overview of the topic and ties it to the Kenyan context.

2. The End-of-Life Problem of EV Batteries

The most common types of batteries used in EVs are lithium-ion batteries (LiBs). This battery type is beneficial for e-mobility since LiBs combine a relatively long life cycle with high energy density, which ensures a power provision over a long duration and thus increases the driving range of an EV. LiBs are furthermore suited for fast charge and discharge while withstanding a high number of regeneration circles and temperature ranges (Chen et al. 2019: 2622, JMK 2019: 7).

As the market for EVs grows, it is estimated that the number of available used EV batteries will increase from 50,000 in 2020 to 150 million in 2035 (Kotak et al. 2021: 2). While LiBs have a longer life cycle than most other battery types, they also ultimately reach their end-of-life (EOL) point in EVs after some time - usually, after 8 to 12 years of usage or after around 200,000 – 250,000 km. The battery capacity is gradually reduced through stressful conditions in the EV such as "extreme operating temperatures, hundreds of partial cycles a year, and changing discharge rates" (Engel et al. 2019). This affects acceleration, range and regeneration capacities of the vehicle and ultimately deems the battery unsuitable for usage in an EV (Zhao et al. 2021: 189, Pagliaro & Meneguzzo 2019: 2).

However, treating LiBs as waste is not an option, considering the environmental impact associated with the battery manufacturing, the hazards of disposing them in landfills as well as the economic benefits promised by re-use and recycling models (Kotak et al. 2021: 2, ESMAP 2020: 1). In fact, when reaching the EoL for usage in EVs, the battery still retains between 70-90% of its power capacity (Zhao et al. 2021: 168). It can thus be removed for application in non-vehicular uses (Reuse). In addition, battery recycling allows to regain valuable raw materials such as lithium, manganese, aluminium, copper as well as the two particularly rare metals cobalt and nickel (JMK 2019: 7 & 15, Kotak et al. 2021: 3).

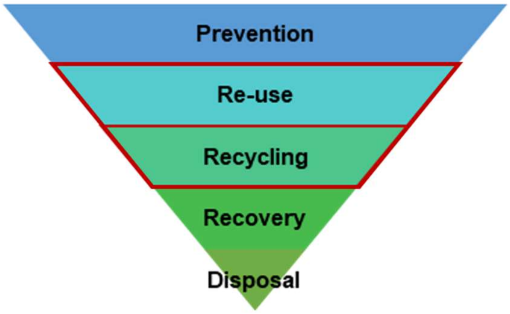

Figure 1: Waste management hierarchy (adapted from Harper et al. 2019: 76)

Reuse means "putting the battery technology as a whole to a second use that is quite distinct from its primary production purpose"

Recycling refers to the „retrieval of specific elements in a produced technology for subsequent use in other technologies, perhaps, including other batteries"

(ESMAP 2020: 8f)

2.1 Prolonged Life: Re-use and Remanufacturing

LiBs that reach their EoL in EVs usually still contain 70 to 80% of the initial energy. While this is not enough for usage in EVs which depend on the battery capacity for range, there are other battery applications that do not have the same requirements as EVs (Zhao et al. 2021: 168). Acknowledging that the end of use of a battery in an EV is not equal to its ultimate end of life in general, such alternative applications are commonly referred to as second-life applications.

2.1.1 Preparation of EV Batteries for Reuse

In order to convey used EV-batteries to their second life, they have to be collected and transported in a safe way. A battery assessment is required in order to check how well the battery works and to determine if it is suitable for re-use. Different second life uses have different requirements. Zhao et al. (2021: 192) list that the battery performance assessment includes visual inspection, verification of battery voltage, assessment of state of health, capability tests and cycling studies (charging and discharging under defined conditions) to observe cell capacity, voltage and physical properties. This procedure is required to identify batteries with similar characteristics in order to assemble relatively homogenous second-life batteries as a more homogenous compilation is easier to manage. After replacing damaged cells as well as modules and after reconfiguration of new modules into packs, a new battery management system[1] must be established that suits the new application purpose (Chen et al. 2019: 2625).

A small share of EV-batteries can potentially be re-used in new EVs after replacement of failed cells. This process is referred to as re-manufacturing and is currently conducted mainly by two companies in the USA (Chen et al. 2019: 2625). Remanufacturing is particularly advantageous because it skips labour intense dismantling processes. Still, a majority of used EV batteries are not suitable for remanufacturing but can be re-used in other applications. The decision which battery to use in what kind of application also has to take into account local conditions to determine if a second-life use can be effective and efficient. This includes the local ambient air temperature, the reliability of infrastructure (e.g. energy grid) but also the availability of fire extinction resources and trained personal to deal with an inflamed LiB (ESMAP 2020: 18).

2.1.2 Second Life Applications

Storing energy from renewable sources is the most common second-life use of LiBs (Kotak et al. 2021: 4). The share of energy from transient, renewable energy sources (such as wind and solar) is increasing globally and also in Kenya which makes energy storage solutions more necessary than ever. Energy storage requires a lower current energy density from the battery package than the use in an EV and is overall less stressful for the battery. It is thus still suitable for second-life batteries (Pagliaro & Meneguzzo 2019: 2, Chen et al. 2019: 2626). Also, storage systems based on used batteries from EVs are more cost-efficient and sustainable than first use battery systems. Such storage facilities can range from small sized applications for residential and commercial storage to large scale industrial facilities that include a few hundred second-life batteries (Zhao et al. 2021: 193).

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[1] The battery management system monitors operational parameters of the battery cells. It can generate an alarm or disconnects the battery if key parameters are exceeded (e.g. too high voltage, overheating). It is a crucial safety system and can also extend the life span of a LiB through reducing stressful conditions that lead to a loss of capacity (Electropedia 2021).

Box 1

Ongoing Development - Second-life Energy Storage Projects in Kenya

Sources: ESMAP 2020: 23, WEEE Centre 2021, Largue 2019

As part of the Faraday Battery Challenge, the Kenyan solar home provider **M-KOPA** explored the second-life usage of LiBs from vehicles for energy storage.

The Kenyan company **BBOXX** worked together with **Aceleron** (battery manufacturer) and **support from the Shell foundation** on testing the second use of LIBs for energy storage. First outcomes point to a superiority of LiBs as opposed to traditional lead-batteries regarding storage performance. BBOXX is thus working on a business model to commercialize the second-life approach and to expand it to other countries.

The **Waste Electrical and Electronic Equipment Centre (WEEE Centre)** in Kenya carries out performance testing and repackaging of old battery components from electronics for remanufacturing. Most of their focus has been with solar batteries.

Aceleron – a reusable battery developing company in the UK - partnered with the fuel producer **Total Access to Energy Solutions (TATES)** in developing second life battery storage systems in Kenya. It mainly focuses on off-grid solutions that provide renewable energy for Kenyans who currently don't have access to electricity. The project runs until 2021 and aims to expand to other African countries due to its success. The costs of 45$ per second life battery unit are able to compete with the cost for lead acid batteries (4$/years) given that they last at least 12 years.

For Kenya, back-up power and off-grid energy storage applications are promising uses. The back-up power from energy storage systems based on used batteries could be used to provide electricity to hospitals and schools in case of power outages. Off-grid applications could be used to provide electricity in remote areas of the country where suitable grid infrastructure is lacking. Here, the battery storage system is connected to an energy source such as a photovoltaic system (figure 2).

Figure 2: Off-grid solar system (Photo from Afrik21 2020)

Commercial projects and pilots for second-life applications have already been started around the world, focusing on China, Japan, Europe and the USA but also including projects in South Africa, Cameroon and Kenya (cf. box 1). Most of these projects are combined ventures of car manufacturers and service providers from the energy sector (Zhao et al. 2021: 196, cf. box 2).

Box 2

Stationary Energy Storage from Nissan and Eaton for Different Scales

Sources : xStorage 2021, Mobility House 2018, Chen et al. 2019: 2626, Engel et al. 2019, Pagliaro & Meneguzzo 2019: 2, Shaffer 2018, Nissan 2016

The car manufacturer **Nissan** cooperated with **Eaton** to develop **xStorage** – an energy storage system that is grid-based and can store energy from renewable sources. xStorage provides home energy storage solutions with second-life batteries from Nissans electric vehicle models. For businesses, larger-scale solutions are available and the system has already proven its scalability to the building-level:

In 2018, the largest European energy storage system based on EV batteries was installed in the **Johan Cruijff ArenA in Amsterdam** in the Netherlands. The xStorage facility in the ArenA is based on 590 battery packs out of which 250 are Nissan LEAF second life batteries. Its storage capacity of up to three megawatt would be sufficient to power several thousand households. The application enables an optimal storage for the solar energy from 4,200 panels on the roof and can also retrieve and store grid energy at low cost during the night. The stored energy can power the stadium for one to three hours during events and is used to balance out peaks in energy demand that occur for instance during energy intense events like concerts that increase the energy demand from 200kW to more than 3000kW.

The xStorage products were firstly introduced in the European market. There, the xStorage Home product includes a 3.5kW storage system based on second life batteries that was available for 3,500€ and a larger 6kW system for 3,900€ (excluding taxes and installation) in 2016. The same storage systems were available for 5,000€ and 5,580€ based on new batteries.

Eaton also has offices in South Africa, Ivory Coast, Morocco, Nigeria and Kenya and aims to expand to the African market. xStorage products were for instance used at the Wadeville facility in South Africa as part of a microgrid solution to deal with unreliable energy supply.

While energy storage can be considered the most common application type, second-life batteries can also be re-used for micromobility such as forklift trucks (pilot project by Audi) or in EV-charging stations (Zhao et al. 2021: 197, Chen et al. 2019: 2625). The repurposing of EV-batteries for EV-charging stations is currently explored in pilot projects in Belgium and Germany, supported by car manufacturers like BMW, Nissan and Renault (JMK 2019: 18, Chen et al. 2019: 2626). A recent estimation of the World Bank suggested that the reuse of second-life LiBs could reduce the costs of setting up EV charging infrastructure by 90% until 2030 (ESMAP 2020: 10).

2.1.3 Profitability of EV Battery Reuse and Re-manufacturing

From an environmental perspective and considering the waste management hierarchy, the re-use of LiBs from EVs provides relevant advantages over landfilling, storage or immediate recycling as it increases the battery life cycle (Harper et al. 2019: 75f). However, the feasibility of putting up a battery re-use economy also depends on the economic profitability and scalability of second-life applications. Due to steadily increasing interest in renewable energy, the demand for energy storage is also growing. It is estimated that by 2030 the global market value of LiB based energy storage alone will be more than $30 billion (Engel et al. 2019). In Kenya and the surrounding East-African region, (battery) energy storage markets are expected to grow due to efforts to increase energy access in rural areas. Battery storage is furthermore of importance in the region as it can provide grid stabilization services and can ideally be combined with the rising share of renewable energy generation (Renewable Energy World 2020, Oirere 2016). As the second-life EV battery capacity is expected to surpass the demand for energy storage by 2030, it is a viable application within this sector (Zhao et al. 2021: 168, Engel et al. 2019). However, the availability of second-life batteries will differ between countries depending on the state of e-mobility expansion and the import of used EVs.

In the end, second-life batteries will have to compete with new battery applications that are expected to become more technologically advanced and cheaper in the future. Research on the US-market suggests that second-life applications will be 30-70% cheaper than new batteries by 2025 and are likely to remain competitive until 2040 even though the cost advantage might drop to 25% (Engel et al. 2019). However, due to higher labour costs, estimations for the price of second-life batteries in the USA cannot directly be transferred to Kenya (cf. figure 3). Zhao et al. (2021: 199) suggests that second-life applications "could remain profitable in countries with high productivity and low labor costs" despite price declines for new batteries. In Kenya, the market perspective for second-life applications might thus exceed the 2040 mark estimated for the US-market.

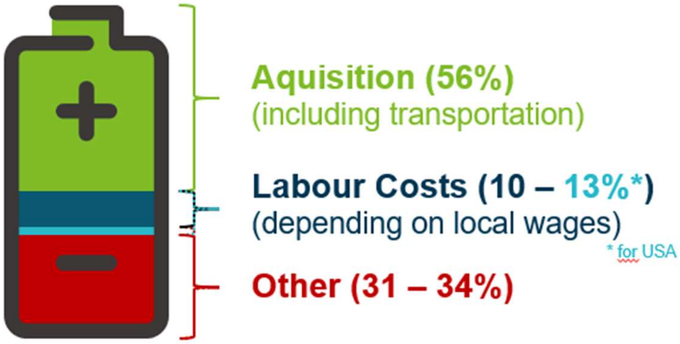

Figure 3: Composition of costs for re-use of EV batteries
(own figure based on data from Zhao et al. 2021: 190ff)

The profitability of second-life applications compared to new battery models also depends on the application type. For instance, the direct reuse of batteries without dismantling of the cells to reduce inhomogeneity lowers the costs significantly (Kotak et al. 2021: 5). A review of several economic analysis of different second-life applications identified a total of 13 profitable re-use opportunities. The biggest market potential was found to exist for energy storage applications for residential use, telecommunication and in office buildings (Zhao et al. 2021: 193ff). The findings correspond to the ongoing increase of commercial projects in these fields (ESMAP 2020: 17f).

2.1.4 Challenges and Advantages of Second-life Battery Applications

Summarizing the advantages and current challenges related to second-life applications suggests that the implementation of a second-life system for used EV batteries is not only economically viable but can also support Kenya's ambition to reach environmental goals and create new job opportunities. National regulations can support the emerging EV-battery-reuse industry and are key to reducing most of the challenges that the industry currently faces (cf. box 3).

Overall, the re-use of LiBs can extend their lifespan by six to 30 years depending on the application (ESMAP 2020: 11). However, second-life applications will ultimately also reach their end-of-life. Re-using EV-batteries can, thus, only be considered as a relevant supplementary strategy regarding the end-of-life of EV batteries that should be implemented before recycling.

Box 3

Summary: Advantages and Challenges for Second-life Use of EV Batteries

Sources: Zhao et al. 2021: 168, 188 & 199, Kotak et al. 2021: 4, Harper et al. 2019: 77, JMK 2019: 19, ESMAP 2020: 11f & 16f)

Advantage	Challenge
Huge global energy (200GWh) and market potential ($30 billion)	Non-standardized battery system and lack of labelling (with more than 165 EV models in the market globally) leads to an increased complexity of battery assessment and complicates re-use *potential solution:* support standardisation and labelling of battery systems (e.g. through import regulations)
Local re-use industry provides independence from current battery manufacturing regions	Lack of battery quality (not all batteries can be used for second life due to their initial design and quality) *potential solution*: support certification and quality regulations - battery manufacturers should already design for an easy disassembly and re-use
Re-use business provides local jobs and supports the local value-chain	Lack of availability of batteries for large application (limited number of used batteries reduces scalability of the business) *potential solution:* used EV-batteries will become increasingly available in the future as the EV market continues to grow; in the meantime, small numbers of EV batteries can be used for home storage solutions
Consumption of less new batteries (e.g. for storage applications) reduces the overall resource consumption and related environmental impacts	Cost reduction and technological improvement of new batteries (competition for second-life systems) *potential solution:* local policies can support and favor second-life applications (e.g. tax benefits), currently second-life applications are more competitive than new batteries
Increased use of EVs and related GHG emission reduction due to cheaper EV ownership costs	
Second-life batteries support affordable energy storage systems that help to boost smart grid projects and renewable energies overall	

2.2 Closing the Circle: Battery Recycling

The components used in LiBs are not only rare and valuable but also potentially harmful for human health and the environment if they are not treated properly after the battery reaches its end of life. Estimations suggest that currently only about 5% of all LiBs are being recycled globally[2] (Woollacott 2021). This leaves a huge number of end of life batteries that are unaccounted for and might pose a fire-hazard if being stored or could be releasing heavy metals and toxic gases into the environment to potentially be absorbed by plants and agricultural products if put into landfill (JMK 2019: 14ff).

At the same time, recycling offers a good opportunity to return valuable materials into the manufacturing process. Recycled battery components are just as efficient as newly mined ones and come with a significantly lower footprint regarding environmental as well as social impacts related to the mining of cobalt and lithium in particular (Harper et al. 2019: 76, Shao et al. 2018: 2, Zhao et al. 2021: 178). For example, the use of recycled battery materials can reduce the CO_2 emissions related to the battery production by 90% and can thus play a vital part in reaching greenhouse gas emission reduction targets (JMK 2019: 15ff).

Considering the scarcity and uneven distribution of critical raw materials, recycling can further be considered as a vital strategic step towards establishing an independent battery manufacturing system (Woollacott 2021, Chen et al. 2019: 2623f).

2.2.1 How does it work?

Prior to the recycling process, a solid collection and transportation system is required in order to ensure enough supply of recycling material and safe shipment to the recycling facility.

Depending on the recycling interest (e.g. high recovery of copper or aluminium or high recovery of all components) different recycling processes are available that have their related advantages and disadvantages. Such processes include:

- Pyrometallurgical processing (smelting)
- Hydrometallurgical methods (involves use of acids and bases to leach materials)
- Direct recycling (mechanical process)

Currently, pyrometallurgical and hydrometallurgical procedures are most common for LiB recycling. The *pyrometallurgical treatment* with heat and flame is a cheap method but produces relevant greenhouse gas emissions while the *hydrometallurgical recycling* with liquids and chemicals is less energy intense but related to technical challenges that increase the costs. Both methods provide a recovery rate of around 50% regarding critical battery materials. Some recycling plants combine pyrometallurgical and hydrometallurgical methods to reach a recovery rate of up to 70% for lithium (Kotak et al. 2021: 6, ESMAP 2020: 16f, Hyunate & Youngsik 2021).

Direct recycling refers to technologies that apply mechanical processes like floating, magnetic separation and suchlike that directly regain the valuable cathode material with minimal input. This technology promises a high return rate and is considered more environmentally friendly. So far, it remains in a lab-state with research ongoing at ReCell and the Faraday Institution in the USA in order to scale it up for industrial use (Oberhaus 2020, Chen et al. 2019: 2638f, ESMP 2020: 12, ReCell 2020: 7, cf. box 4).

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[2] Detailed figures about the treatment of LiBs (recycling, reuse, landfill, storage) are missing. The most mentioned estimation states a share of 5% for recycling. The number might be considerably lower in some parts of the world (Woollacott, 2021).

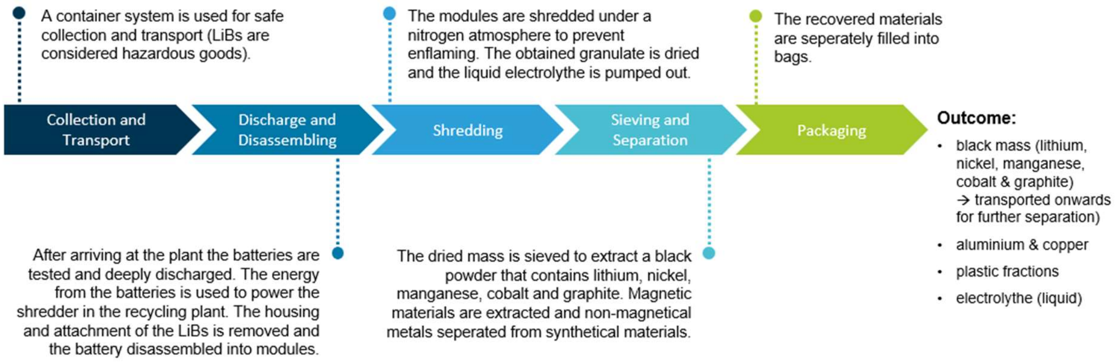
Box 4

Global Pioneers of LiB Recycling

Sources: Harper et al. 2019: 79, Pagliaro & Meneguzzo 2019 : 3ff, Zhao et al. 2021 : 185f, FORTECH 2021

Current cutting-edge recycling technologies for LiBs include those used at **Recupyl** (France), **Akkuser** (Finland), **Duesenfeld** (Germany), **Retriec** (USA/Canada), **Li-cycle** (USA) and **Redwood** (USA). The recycling procedures of these companies are known for combining high recycling rates with good environmental standards and are thus also referred to as *green recycling technologies*.

Green recycling follows a combination of mechanical and hydrometallurgical processes that slightly differs between the different companies but mainly involves five basic steps:



A container system is used for safe collection and transport (LiBs are considered hazardous goods).

After arriving at the plant the batteries are tested and deeply discharged. The energy from the batteries is used to power the shredder in the recycling plant. The housing and attachment of the LiBs is removed and the battery disassembled into modules.

The modules are shredded under a nitrogen atmosphere to prevent enflaming. The obtained granulate is dried and the liquid electrolythe is pumped out.

The dried mass is sieved to extract a black powder that contains lithium, nickel, manganese, cobalt and graphite. Magnetic materials are extracted and non-magnetical metals seperated from synthetical materials.

The recovered materials are seperately filled into bags.

Outcome:

- black mass (lithium, nickel, manganese, cobalt & graphite) → transported onwards for further separation)
- aluminium & copper
- plastic fractions
- electrolythe (liquid)

Figure 4: Duesenfeld recycling process (own figure based on Duesenfeld 2021, VW 2021 & CNBC 2021)

This recycling procedure offers a recycling rate of 95-98% for nickel, cobalt, aluminium and graphite and up to 80% for lithium. However, this technology is currently comparatively costly. Further research is needed to introduce the technology at a large-scale and commercial level.

For countries of the global south, the GIZ project *Towards a secure and eco-friendly circular economy of lithium batteries* is dedicated to developing a LiB recycling system in Costa Rica in collaboration with the waste management and recycling company **FORTECH**. The public-private-partnership has set an ambitious goal to reach a recycling rate of 100%. The project started in December 2020 and will run until 2023.

2.2.2 Profitability of EV battery recycling

> ***"It is the right thing to do.***
> ***But there is also money to be made,***
> ***and that's the attraction"***
>
> *(Jeffrey Spangenberger, director of ReCell research center, cited in Kumagai 2021)*

The final revenue of battery recycling depends on the composition of the LiB, on the recycling process and on raw material prices as well as on the price and availability of end of life batteries. Whether LiB recycling is a promising business case significantly varies among countries at the moment. China and South Korea are main players in the emerging global LiB recycling business as end of life EV batteries are sufficiently available there. In addition, low labor costs combined with relatively advanced recycling technologies ensure good recycling rates at moderate costs (Zhao et al. 2021: 179, Kumagai 2021).

Researchers broadly agree that recycling will become a business case in the future in further countries where it is currently not yet profitable (cf. box 5). This will be driven by technological improvements as well as by the increased availability of EV batteries, especially in countries like Kenya that are planning to expand e-mobility (Chen et al. 2019: 2623). Even though, this might take some time. Second-life applications of EV batteries as described in the chapter before can bridge the gap until recycling of EV batteries becomes widely profitable.

The development of hydrogen vehicles might potentially pose a risk to the sustainability of the battery recycling market as it might reduce the demand for EV batteries and the required raw materials accordingly. Likewise, ongoing research on new battery technologies that require less cobalt – the most valuable material in the battery – will reduce the value of the recycling outcome and thus the margin of profit. However, recycling is likely to remain profitable despite these trends (Zhao et al. 2021: 181, Oberhaus 2020).

Box 5

Emerging Battery Recycling Market in India

Sources: JMK 2019

Among emerging economies and developing countries, India is considered a pioneer in battery recycling. By promoting a strong Indian EV battery recycling industry, India is trying to reduce its dependency on China for the import of LiBs that came as a result of the county's Electric Mobility Mission Plan 2020 leading to the development of a significant market for electric vehicles.

Establishing a local recycling economy for EV batteries not only reduces dependency on other countries as well as the environmental burden and hazards related to the disposal of LiBs but also ensures a strategic supply of crucial raw materials for India. First battery manufacturing plants were already set up in the country. In the future, battery manufacturing in India will largely depend on raw materials obtained through recycling within the country. As of 2019 four major companies were already building recycling systems and eight e-waste recycling companies were also working on expanding their business towards LiBs.

At the moment, the costs for recycling in India are still rather high (around 1.20 – 1.35US$/kg) and investment costs are thus only recovered after 5 years. However, the LiB recycling market is expected to pick up speed already by 2022 and is estimated to develop into a $1,000 million opportunity.

In a country like Kenya, where e-mobility will likely be supported by the government as a means to reducing transport related greenhouse gas emissions in the future, it is advisable to not only look at the profitability of EV battery recycling itself but to also consider the alternative cost of not setting up a recycling system. As LiBs are considered hazardous waste, their export is subject to the Basel Convention and the Bamako Convention for Africa. They can only be shipped if the country of destination has facilities for their treatment and the transport has to follow security standards that lead to high shipment costs and long latency for required permits (UNEP n.y., UNEP 2021, Efficiency for Access Coalition 2021: 57). For Kenya, this poses the risk of high follow-up costs for importing used EV vehicles as EoL EV batteries will have to be shipped to recycling plants in Europe, the USA, or Asian countries in the absence of a local recycling system. Experience from Nigeria indicates that conducting the first steps of LiB recycling within the country already significantly reduces these shipment cost and generates profits (cf. box 6).

Box 6

Experience from LiB Recycling- Hinckley, Nigeria

Sources: Efficiency for Access Coalition 2021: 54ff, ESMAP 2020

In collaboration with the Chinese company Taisen, Hinckley set up a recycling facility for end of life LiBs from off-grid solar devices and laptops in 2021. Apart from setting up a recycling plant, Hinckley collaborates with informal e-waste collectors and recyclers, providing training and access to medical assistance and acting as a purchaser for the collected materials. The company applies a mechanical recycling technology that is a "clean, low energy solution ideal for the African environment" (Efficiency for Access Coalition 2021: 54). The "black mass" (a mixture of lithium, nickel, manganese, cobalt and graphite) that remains after the procedure is shipped to Europe and sold at London Metal Exchange rates. Battery manufacturers and the chemical industry can further separate the "black mass" and use the regained material for their production.

This procedure significantly reduces the shipping costs. While five tonnes of unprocessed batteries (hazardous good) cost US$ 3,500 for shipping, the same weight of "black mass" (not a hazardous good) can be shipped for US$ 3,000. As five tonnes of "black mass" are the outcome of the recycling of 50t of unprocessed batteries, this is equal to a total reduction of shipment costs by 32,000 US$.

At the same time, the "black mass" can be sold to generate additional profit: first estimations for different kinds of LiBs indicate that there is a potential revenue of USD 400-1900 per tonne of black mass depending on the composition of the battery especially regarding the amount of cobalt within the battery (figure 5).

	Cost of Shipment	**Purchase Price**	**Revenue** (excluding overhead costs of operation)
Black mass from laptops/tonne (35% cobalt)	600US$	2000-2500US$	1400-1900US$
Black mass from off-grid solar/tonne (5% cobalt)	600US$	1000-1500US$	400-900US$

Figure 5: Revenue of recycling of different battery types by Hinckley, Nigeria
(slightly adjusted from Efficiency for Access Coalition 2021: 58)

2.2.3 Setting up a recycling system

As scholars predict that EV battery recycling might not remain an option but become a necessity in the future due to the beforementioned reasons, it seems advisable for governments to prepare for setting up a recycling system (Zhao et al. 2021: 198, Pagliaro & Meneguzzo 2019: 6). Experience from other countries suggests that starting with LiBs from other appliances than EVs, such as solar-waste, mobile phones and laptops, can help to put in place infrastructure and human capacity that can be applied to EV batteries once they become available at relevant scale (Efficiency for Access Coalition 2021: 54f, ESMAP 2020: 23, Schloenvoigt 2020). This is already happening in Kenya, providing a useful local knowledge base (cf. box 7). Bringing together the right stakeholders is an important starting point: experience from other countries indicates that car manufacturers can be relevant partners for setting up a recycling industry for LiBs as they are interested in re-using the raw materials in the production of new EV batteries (Agora Verkehrswende 2017: 60).

Box 7

Pioneers of LiB Recycling and E-Waste-Management in Kenya

Sources: EWIK 2021, WEEE Centre 2021, WeTu 2021, Efficiency for Access Coalition 2021: 55f

WeTu has established a collection and recycling system for its solar powered fishing lamps. In the future, they intend to develop a circular economy system for their WeMobility products such as electric 2- and 3-wheelers. Apart from second use applications this also includes setting up a collection and recycling system for EV batteries.

E-Waste initiative Kenya (EWIK) is an NGO that is concerned with e-waste and recycling, particularly in the informal sector. It is already involved in the collection of and recycling of e-waste and provides trainings for the safe handling of e-waste. Its activities further include collaborations with the private sector for effective e-waste management.

Apart from being engaged in reuse projects (as mentioned before), the **WEEE Center** also focuses on the safe handling and collection of electronic waste and proper disposal or recycling. Its activities include trainings, awareness raising and disposal of e-waste in their recycling plants.

2.3 The Circular Economy of EV Batteries

It has been established so far, that the reuse of LiBs from EVs in second-life applications is already profitable and a solid way of prolonging the life of batteries. As can – however – only postpone but not omit the EoL problem it is mainly a supplementary strategy that postpones the need for recycling to a point in time when technological improvements will have made recycling profitable on a large scale (Kotak et al. 2021: 12, Harper et al. 2019: 76). Reuse and recycling can thus ideally be combined and interlinked within a circular economy system to provide a comprehensive solution to the growing EoL problem (cf. figure 6). Such a circular economy system aims for an optimised retention of batteries and raw materials to save resources. Ideally, the reuse and recycling of LiBs will be considered during every step of a battery's life cycle. "This will involve smart integration of batteries with the electricity grid, prolongation of their service life through repairs and refurbishment, reuse for other applications such as stationary electricity storage and high quality recycling" ([Kadner 2020](#)).

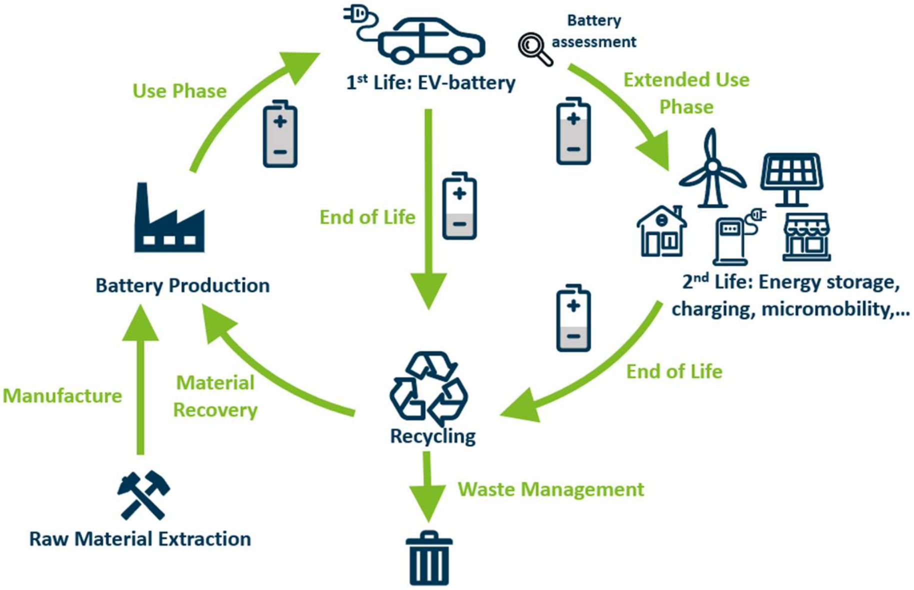


Figure 6: The EV-battery circular economy (own figure heavily based on Kotak et al. 2021: 2)

In practice, such a comprehensive circular economy system does not need to be set up completely within one country alone but can involve cooperation among different countries. For Kenya, particularly the steps after the first life within the EV are of importance: Within a circular economy system the LiBs firstly undergo a battery assessment to determine basic characteristics and the state of health of the battery. Based on the outcome it is decided if the LiB can be used in second-life applications or should be recycled directly (Chen et al. 2019: 2623, Kotak et al. 2021: 10). Ideally, a multitude of second-life applications would be available (energy storage, use in charging station, etc.) so that LiB can be used for the most appropriate and profitable application based on the prior assessment.

However, all batteries will reach their end of life ultimately and will need to be recycled to regain valuable material. As described before, not all steps of the recycling process have to be conducted within Kenya itself. The processing of LiBs to the stage of "black mass" would already significantly reduce costs and effort related to the export of LiBs for recycling. The recovered material can be used for battery production or in the chemical industry where it provides a relevant alterative to raw materials from mining thus reducing the related environmental and social impacts (ESMAP 2020: 10).

Creating such a closed circular economy for EV batteries contributes greatly to reducing greenhouse gas emissions from the transport sector. In fact, it could "enable 30% of the required reductions in carbon emissions in the transport and power sectors" (Zhao et al. 2021: 174). It further offers significant economic potential and employment opportunities.

Considering the potential hazards related to the EoL problem that will be particularly visible in countries that rely on second-hand vehicles to built up their EV fleet as well as the multiple benefits and business potentials (e.g. energy storage), "Africa is one of the regions that would most directly benefit from a robust circular economy program for Li-ion batteries" (ESMAP 2020: 23).

2.3.1 Developing a Circular Economy for EoL EV batteries

When e-mobility gains traction in a country such as Kenya, this in turn generates battery waste. Hence, it is important to promote both the uptake of e-mobility as well as the circular economy system around it. Evidence from other case studies suggests that a combination of legislation, capacity building and cooperation with car manufacturers and battery producers can support the establishing of a circular system (cf. box 8).

The draft national e-waste management strategy for Kenya makes recycling a priority. It lists companies such as Waste Electrical and Electronic Equipment Centre (WEEE Centre), Sinomet Kenya, Sintmund Kenya and E-waste Initiative Kenya (EWIK) that have been licensed to carry out e-waste recycling; including for batteries. Infrastructure for e-waste management and absence of frameworks for EoL are some of the issues identified as needing intervention.

Box 8

Recommendations for Setting Up a Circular Economy for EV Batteries

Sources: Harper et al. 2019, ESMAP 2020, Efficiency for Access Coalition 2021, Kotak et al. 2021, UNEP 2020: 53ff
Zhao et al. 2021, Zheng et al. 2018, Chen et al. 2018, Pagliaro & Meneguzzo 2019, JMK 2019

Legislations and policy

- Support recycling legislations (Extended Producer Responsibility, ban landfilling of LiBs) (e.g. *EU Directive 2000/53/EV bans landfilling, Australia's National Stewardship Scheme 2020 requires manufacturers to pay for end of life processing per battery.*
- Develop standards for recycling procedure and second-life applications to ensure security (e.g. *EU Battery Directive 2006/66/EC sets standards and required recycling rates for LiB recycling)*
- Support initiatives for standardisation and labelling of EV batteries *(e.g. EU Directive 2000/53/EV sets requirements for vehicles to be designed in a way that they can easily be recovered, re-used and recycled, In China EV manufacturers are required to use a unique ID to trace their batteries since 2018)*
- Consider regulations on EV importation (i.e. on age of vehicle, state of health of the battery, requirements for labelling and standardisation of the battery) (e.g. Sri Lanka supports the import of used EVs but requires emission testing and roadworthiness inspections, Egypt only allows the import of EVs that are less than 3 years old)
- Create legal security for use of second-life applications
- Consider subsidies/tax benefits for battery recycling and second-life businesses *(e.g. Japan since 2000)*

Networking

- Include car manufacturers and battery producers into process *(e.g. Nissan and Volkswagen are active in second-life applications and battery recycling, Hinckley in Nigeria)*
- Exchange and collaborate with other countries and aim for a regional approach
- Collaborate with already existing initiatives in the country *(e.g. WEEE, WeTu, …)*

Capacity building

- Learn from existing examples (LiB recycling for mobile phones, laptops, Solar E-Waste) to expand knowledge
- Invest in research and technology of battery recycling and second-life approaches *(e.g. China set up a recycling research plan in 2015)*
- Start pioneer plants for recycling that can be expanded to meet the demand for EV batteries

3. Conclusion

With the increasing uptake of e-mobility, the treatment of used EV batteries will become a challenge not only in Kenya but globally. While research on recycling technologies for LiBs is ongoing and showing promising results, the technology is not yet ready for large-scale applications. Additionally, the current lack of availability of EV batteries hinders the development of profitable recycling business models. Second-life applications can act as a buffer to prolong the life of EV batteries until profitable recycling solutions are available. They are, however, not to be considered as interim solutions, but rather actions that offer relevant ecological and economic benefits and should therefore always be sought before recycling.

Ultimately, second-life applications should be integrated into a larger circular economy around end of life EV batteries. While currently recycling activities are mainly happening in Europe, the USA, China and South Korea, pioneer projects from India and Nigeria show that recycling and second-life application is also a viable business model in the Global South.

In Kenya, NGOs and start-ups have already started to engage in the recycling business and are pioneering second-life applications. To strengthen similar business models, the country can learn from legislations in the EU, Australia, China and Japan and should aim to develop a strategy for setting up a battery management system based on the principles of a circular economy.

As e-mobility is currently starting to develop in Kenya, the country is at an optimal position to develop a second-life and recycling system in parallel to the increased uptake of EVs. This will help limit negative impacts related to the end of life problem of EVs and can instead provide environmental and economic benefits.

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Registered offices
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Friedrich-Ebert-Allee 36+40
53113 Bonn, Germany
T +49 61 96 79-0
F +49 61 96 79-11 15
E info@giz.de
I www.giz.de

Authors:
Verena Knöll, Bonn
Kwoba Herman, Nairobi
Nadja Taeger, Bonn

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Verena Knöll, Bonn

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Deutsche Gesellschaft für
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Sitz der Gesellschaft
Bonn und Eschborn

Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Deutschland
T +49 228 44 60-0
F +49 228 44 60-17 66

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn, Deutschland
T +49 61 96 79-0
F +49 61 96 79-11 15

E info@giz.de
I www.giz.de