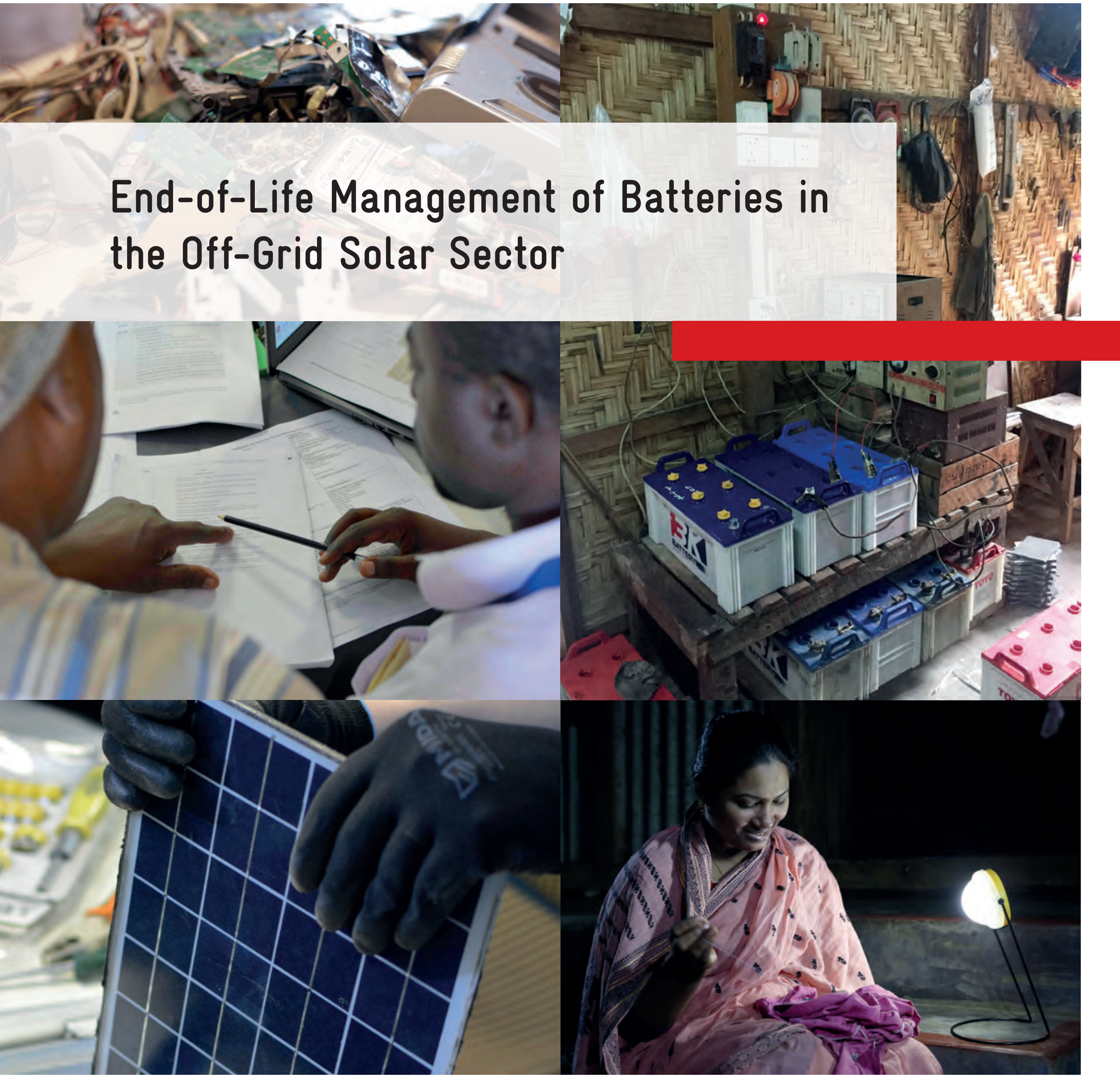
End-of-Life Management of Batteries in the Off-Grid Solar Sector



How to deal with hazardous battery waste from solar power projects in developing countries?

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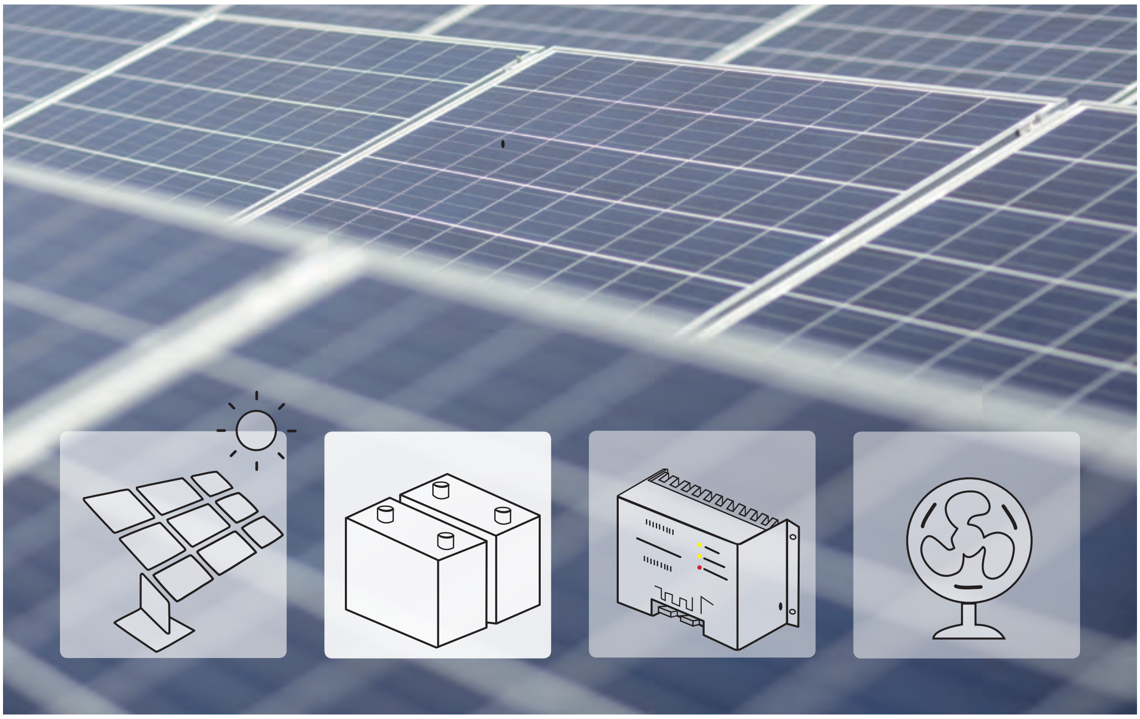

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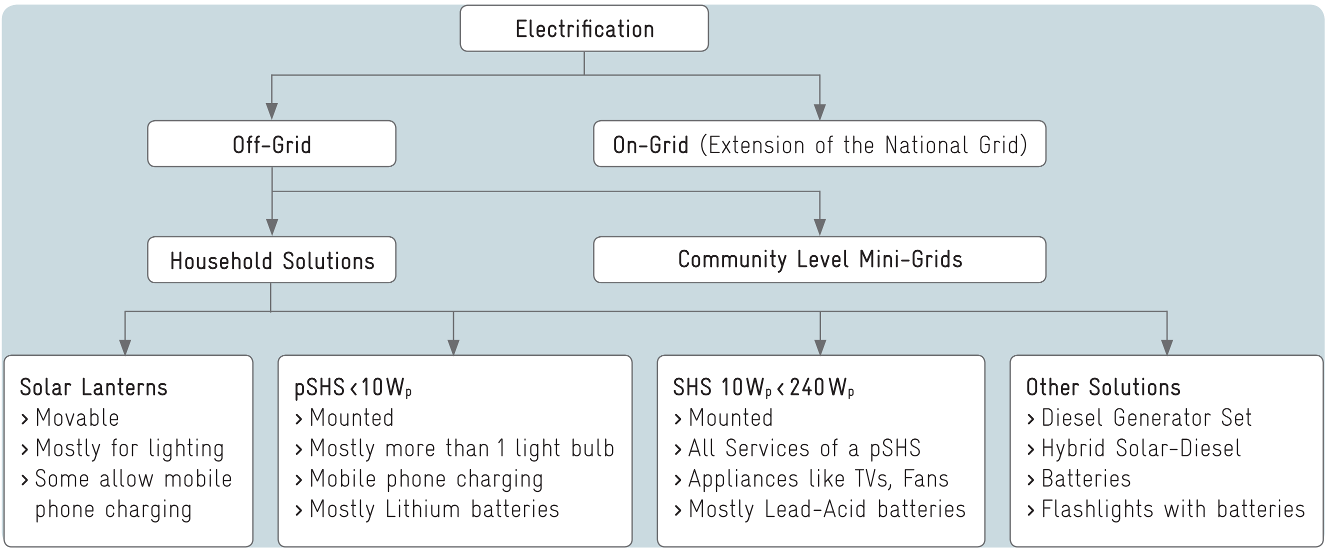
LIST OF ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
EPR	Extended Producer Responsibility
LAB	Lead-acid battery
LFP	Lithium-iron-phosphate
LME	London Metal Exchange
LMO	Lithium-manganese-oxide
PAYG	Pay-As-You-Go
PCB	Printed circuit board
PE	Polyethylene
PRO	Producer Responsibility Organization
PS	Polystyrene
PVC	Polyvinyl chloride
RoHS	Restriction of Hazardous Substances
SHS	Solar home system

1 INTRODUCTION

In order to achieve Sustainable Development Goal No. 7 on affordable and clean energy for all, many developing countries initiated ambitious energy access programs that are often supported by the international donor community. Many of these government programmes follow a combined strategy encompassing grid extension, establishing mini-grids, as well as the distribution of solar home systems (SHS) and solar lanterns in remote rural areas with no connection to the electricity grid (off-grid).

Figure 1/1: Electrification pathways Source: Adapted from Batteiger and Rotter 2018



While energy-access projects undoubtedly have numerous positive development effects on newly electrified communities, they also bring new challenges related to waste management. These challenges are linked to the fact that equipment used for mini-grids and SHS, as well as the electrical and electronic devices powered by the new systems, will sooner or later become waste. And these waste types (commonly referred to as e-waste and battery waste) have more or less hazardous properties and require special treatment and disposal.

E-waste and battery waste are already known to be a challenge in many developing countries and emerging economies with serious hot spots in many urban areas where collection and recycling is often conducted by informal sectors with little regard to emission control and impacts on human and environmental health.

If these challenges are not taken into account by energy-access projects, related problems might soon expand to rural communities. But this negative scenario should not be used as a reason to slow down energy access efforts. In turn, it is known that many energy-access projects encompass much more than supplying equipment to off-grid areas and often also initiate transformative change in various other fields of daily life and community interaction. Thus, energy-access projects can also serve as a pathway to introduce effective modern waste management systems in areas that have no or limited experience with complex municipal and hazardous waste.

This paper aims to introduce the realities of managing e-waste and battery waste in the context of developing countries, with a specific focus on energy access projects. While chapter 2 gives an overview on the characteristics and required management pathways of most important e-waste fractions from off-grid power installations, chapters 3 to 5 specifically focus on the management of waste batteries from mini-grids and SHS. This focus is justified by the fact that batteries are typically the components with the shortest lifespan. Thus, it is the first waste fraction generated in large volumes only a few years after introducing mini-grids and SHS to a region. On top of this, waste batteries are associated with particularly pronounced environmental and health concerns so that this waste stream requires particular attention by energy-access projects and wider decision-making circles.

Solar electrification brings numerous positive impacts, but also creates e-waste that requires special treatment and disposal.

Off-grid solar power installations such as mini-grids and SHS are composed of photovoltaic panels, control devices (charge controller, inverter…), plastic or metal casing and switches as well as one or more batteries. In addition, various devices such as lamps, fans, radios and TVs are commonly used with SHS and mini-grids, as shown in Figure 2/1. The various components are connected by cables. Solar lanterns are integrated products, containing a PV panel, battery and light. Table 2/1 gives an overview on typical lifetimes[1] and material compositions of these devices.

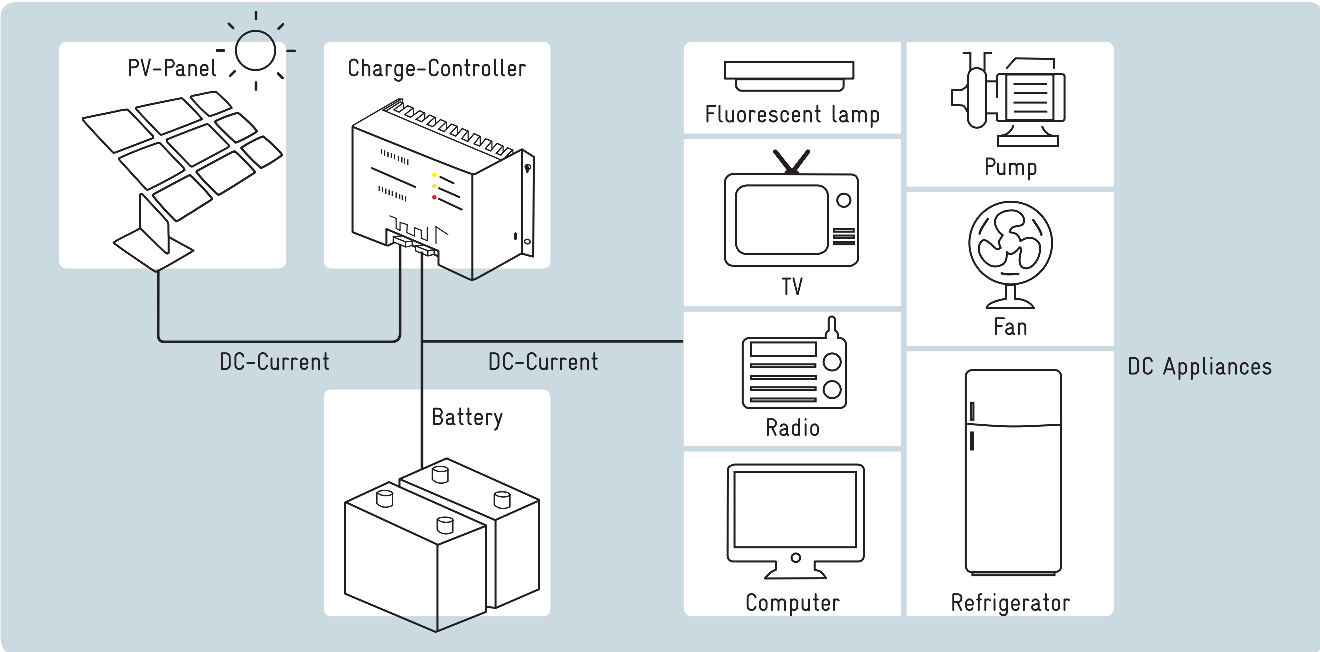
Table 2/1:
Indicative life-times and material compositions of off-grid solar power installations
Source: Own compilation

Component groups	Expected life-times	Typical material compositions
PV panels	> 10 years	Crystalline silicon, glass, aluminium, copper, trace elements (indium, tin, gallium….)
Control devices	5 – 15 years	Printed circuit boards, solder paste, various electrical and electronic components, plastics…
Batteries	2 – 6 years	Lead-acid batteries: Lead, lead-oxide, plastics, electrolyte (sulfuric acid) Li-ion batteries: Graphite, various organic substances, copper, aluminium, lithium, plastics…
Cables	> 10 years	Copper, plastic insulation
Equipment (lamps, radios, fans, TVs…)	2 – 10 years	Various plastic types, aluminium, copper, various electrical and electronic components (microchips,
Solar Lanterns	3-5 years	PV panel, Li-ion battery, LEDs, printed circuit board, plastics.

SHS PV panel on roof top
© GIZ | EnDev Peru

1 Life-time data is indicative only and might vary significantly depending on the quality of individual devices, the type and intensity of use and the general use-conditions (temperature, moisture etc.).

Figure 2/1: Example of a typical solar home system Source: Own figure



While end-of-life management of batteries is analysed in more detail in chapter 3, the following sections give a rough overview on the end-of-life characteristics and challenges related to the other component groups.

2.1 PHOTOVOLTAIC PANELS

Most photovoltaic panels are based on crystalline silicon, which have an indicative material composition as displayed in Table 2/2.

Due to the dominance of glass in the material composition, crystalline silicon panels are commonly treated by glass recycling facilities. More specific recycling processes have been developed in pilot scale plants and only few of them have recently been up-scaled to larger plants.

All recycling processes start with an initial dismantling of the modules to recover the aluminium frame and connecting cables. Further recycling steps mostly focus on the mechanical separation of the glass from silicon wafers and back-foils. The glass has high material qualities but is often difficult to be perfectly liberated from other materials such as plastic foils and silicon wafers, which can negatively impact the quality of the glass output fraction. Many glass recycling industries pass on residual materials (e.g. glue, back-sheet, wafers) to co-processing in the cement industry. In a new recycling plant in France, also some of the plastics and silver is recovered from the panels (Reuters 2018).

Table 2/2:
Indicative material composition of photovoltaic panels (crystalline silicon)
Source: Kernbauer & Hübner 2013; Sander et al. 2007

Component/material	Weight-%	Further information
Glass	74.16 %	Front-glass
Aluminum	10.30 %	Frame
Ethylene-vinyl acetate	6.8 %	
Back-sheet	3.8 %	Various types of plastic-foils (including fluorinated plastics) to protect assembly from moisture etc.
Glue	1.2 %	
Silicon	3.0 %	Wafer with a thickness of 160 - 200 μm
Copper	0.57 %	Wires & contacts
Tin	0.12 %	Contact layers
Lead	0.07 %	Contact layers
Silver	0.0004 – 0.0006 %	Contact layers

It has been proven that the recovery of silicon wafers for reuse purposes is also possible. This can be done by controlled burning of the glue and foils and the chemical etching of intact wafers. While the process is suitable to recover intact wafers from older PV modules, more recent panels use much thinner wafers, which are much more difficult to be recovered undamaged. Although damaged and broken wafers can be used in metallurgical smelting processes or as a source of silicon metal production, both uses are associated with very limited economic returns (Kernbauer & Hübner 2013), which leads to a situation in which recycling of PV panels is associated with net-costs (D'Adamo et al. 2017).

In this context, it is quite likely that future recycling will mostly focus on the recovery of aluminium, copper and glass. As the material value of these fractions is limited, it is likely that treatment costs will in most cases exceed the revenues from the recovered raw materials. In this context, it needs to be considered that many crystalline silicon panels contain lead-based solder paste for contacting the individual wafers. In case panels are not collected or recycled, or only with the above mentioned focus (recycling of aluminium, copper and glass) this hazardous solder is most likely disposed with other residues. As there are alternatives to lead-based solder paste (e.g. tin-silver), the use of such lead-free panels should be considered. It is noteworthy that thin film solar cells are often based on cadmium telluride. Due to the hazardous nature of cadmium, collection and recycling of such types has a high priority but is not explored in more details here.

2.2 CONTROL DEVICES

Control devices encompass charge controllers, inverters, metering devices as well as DC-DC-converters used for powering low-voltage DC-devices (e.g. LED-lamps, mobile phone charging). Control devices usually consist of printed circuit boards (PCBs) mounted with electrical and electronic components, which are built into one or more housings. The assemblies encompass a broad range of materials, including some metals such as aluminium and copper. Silver and tin might be used in lead-free solder and traces of gold and palladium is commonly used in some electronic devices. At the same time, the assemblies usually also contain substances of concern such as brominated flame retardants in plastic components. While heavy metals such as lead, cadmium and hexavalent chromium have mostly been phased-out in electrical and electronic equipment in markets such as the EU, California and South-Korea through so-called RoHS policies[2], these elements might still be in use in devices manufactured for countries and world regions where no related regulations exist or are enforced.

Control devices at a solar installation at a Health Centre, Ethiopia © GIZ | EnDev Ethiopia

End-of-life PCBs as well as other electronic components can be recycled in integrated smelters that operate at large scale in countries such as Belgium (Umicore), Germany (Aurubis), Sweden (Boliden), Canada (Xstrata) and Japan (Dowa). These smelters recover copper, gold, silver, palladium and a wide range of other embedded metals. Plastics of PCBs serve as a source of energy and as reduction agent in the smelting process. Residual materials including iron, aluminium, silicon and ceramics move into the slag phase. Slags are commonly used in the construction industry (e.g. road construction).

2 RoHS stands for Restriction of Hazardous Substances and is the acronym of a substance restriction policy first introduced in the EU in 2003 through Directive 2002/95/EC.

Printed Circuit Boards (PCBs) from waste computers
© GIZ | Daniel Hinchliffe

Recycling of PCBs is also possible with hydrometallurgical leaching-processes that can either be applied at industrial scale (they are in many cases part of the refining processes of modern integrated smelters) or at a small backyard scale focusing on extraction of one or two elements, usually those having high economic value like copper and gold. Various YouTube tutorials inform about practical steps of these hydrometallurgical processes to recover precious metals using various hazardous chemicals such as cyanide and mercury, which can cause major health and environmental impacts. Here it must be stressed that hydrometallurgical processes, especially if rudimentary conducted in small backyard processes, can recover only some of the contained materials and usually do not provide a solution for the hazardous materials. Therefore, hydrometallurgical methods have to be regarded as critical from an environmental perspective.

The end-of-life value of PCBs varies greatly so that this scrap fraction is commonly classified into high-, medium- and low-grade PCBs. While high-grade PCBs have quite high precious metal contents and can mostly be found in IT-equipment such as computers and mobile phones, medium-grade PCBs are mostly mounted with a mix of IT- and electrical components. Low-grade PCBs contain only little, if any precious metals and can mostly be found in electrical equipment, and devices such as analogue TVs and small mixed e-waste (McCoach et al. 2014). End-of-life PCBs from control devices are mostly low-grade and therefore have a limited economic value that is often insufficient to compensate transport costs to end refineries.

2.3 CABLES

Cables have one or more metal cores (mostly from copper) that are insulated with plastics such as PVC or PE. Insulation plastics commonly contain additives, in particular plasticizers. Recycling is motivated by the quite attractive market price of copper and copper scrap.

For recycling the metal cores need to be liberated from the insulation material. To do so, many small scale recyclers in developing countries and emerging economies refer to open burning of cables, which causes emission of highly toxic dioxins and furans. While this method does not require much labour input or investments into machinery, it is associated with severe pollution (see image on next page).

Environmentally sound methods of cable recycling use mechanical processes such as cable stripping or cable granulation. Cable stripping is a common method for medium and thick cables with solid cores but is unsuitable for thin cables and cables with multiple thin wires. While the covered copper can be sold to copper refineries, there is often limited demand for the insulation material.

Cable fires in Ghana
© Öko-Institut e.V.

2.4 / OTHER ELECTRICAL AND ELECTRONIC EQUIPMENT

Equipment commonly powered in off-grid households and mini-grids encompass LED lamps, TVs, mobile phones (charging), refrigerators, fans, water pumps and radios (Efficiency for Access Coalition 2017). Many of these devices contain components that have to undergo separate treatment at their end-of-life as unsound recycling and disposal would cause potential harm to human and/or environmental health. Waste from the above mentioned equipment is commonly classified as 'e-waste' or waste electrical and electronic equipment (WEEE).

Collection and recycling of e-waste is a complex field that cannot be analysed in more detail in this report. Generally, it is noteworthy that some e-waste fractions are of high interest to the recycling industry, in particular copper, aluminium and high-grade PCBs (see section 2.2). Other fractions have a low and some even a negative material value as sound end-of-life management is associated with net costs. Usually, such negative-value fractions are only collected and recycled if this is encouraged and enforced by appropriate legislation and a financing scheme that enables recyclers to earn an income for the service of a full environmentally sound management. In case such a framework is not in place, collection and recycling activities will most likely only focus on valuable factions while other fractions are disposed uncontrolled.

Off-grid solar power installations heavily rely on batteries that allow storing electricity generated during daytime for night-time demand. Depending on the size of individual installations, required battery storage capacity ranges from 9 Wh for small PicoPV systems to typically more than 1 MWh for large mini-grids. Until recently, energy-access projects almost exclusively referred to the use of lead-acid batteries as this technology is widely available, robust and cheap. In recent years, development of Li-Ion battery technologies as well as falling prices generated a situation in which many projects started to consider the use of Li-based battery technologies.

In order to support decision-making for or against certain battery types, this chapter describes the most relevant battery characteristics relevant for end-of-life management.

3.1 / LEAD-ACID BATTERIES

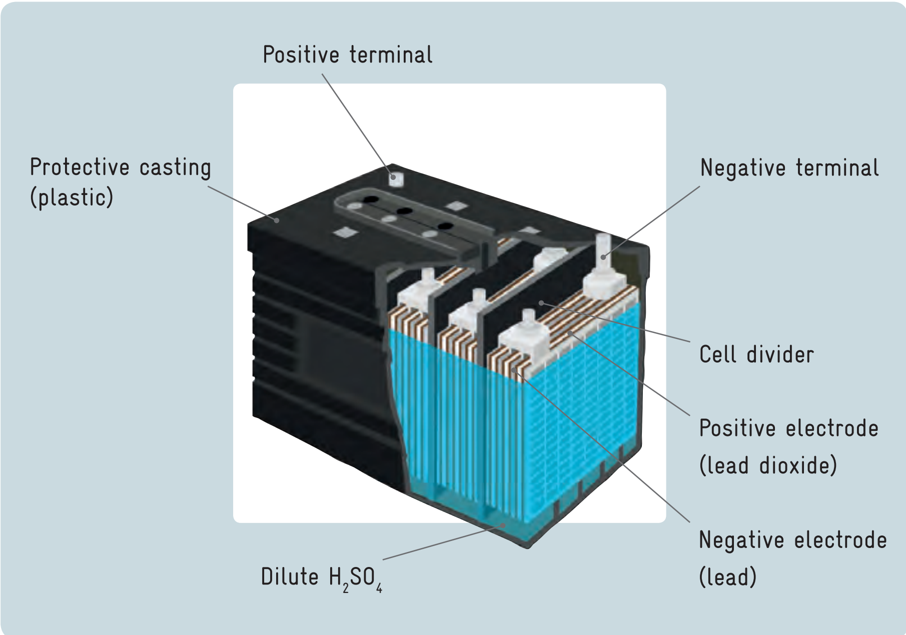


Figure 3/1: Typical structure of a lead acid battery
Source: Chemistry Libre Texts (2018)

3.1.1 Types, prices & life-times

Lead-acid batteries (LABs) are manufactured for various purposes, including the automotive sector and stationary power storage. It is notable that starter batteries for automotive applications are specifically designed to provide short power bursts and not for prolonged power supply. Thus, automotive LABs are inappropriate to be used for solar power applications. In case such batteries are (despite their limitations) used for SHS, battery life-times are commonly as low as 1 or 2 years[3]. Despite this disadvantage, automotive LABs are often used in SHS purchased and installed by private consumers that operate independently from energy-access projects. This is mostly due to the widespread availability as well as cheaper purchasing prices.

For solar power applications deep-cycle LABs are available and commonly used in related projects. Due to more active material (lead), the purchasing prices of such batteries are typically around 20% higher than for automotive LABs. Battery life-times commonly range between 2 and 5 years.

3.1.2. Toxicity potential & safety risks

Around 65% of the weight of lead-acid batteries is lead and lead-oxide, and 10–15% sulfuric acid. Lead is a highly poisonous heavy metal that has numerous adverse effects on various human organs when swallowed or inhaled. Elevated exposure to lead can cause severe damage to brain and kidneys and can severely limit the development of children's brains. Lead-poisoning can cause a wide range of symptoms and can ultimately lead to death. The sulfuric acid is also of concern as it can cause skin burns and eye damage when brought into direct contact with humans. Unsound disposal of sulfuric acid contributes to an acidification of the environment.

During the use-phase, the hazardous constituents of the battery are usually well encased so that emissions to the environment and direct contact with humans are unlikely[4]. Furthermore, the use of lead-acid batteries is comparably safe as there are low risks for overheating and fire. One possible safety risk is associated with overcharging of valve-regulated LABs that have non-functioning or blocked valves. The electrolytic processes in the battery can cause a build-up of pressure and – in case this pressure is not released through valves – cause an explosion.

3.1.3 Recycling practices & infrastructure

Due to their high lead content and the quite stable and attractive world market prices for lead, waste lead-acid batteries and lead-scrap are collected and recycled all over the world – even in settings where collection and recycling is not supported

3
All life-time information of this report is indicative only. Battery life-times depend on a number of factors, including battery quality, charge management and exposure to physical stress and heat. Thus, individual battery life-times might significantly deviate from the indicated ranges.

4
The situation is different during the recycling process, which necessarily involves the breaking of the battery case and the sorting of main materials (see section 3.1.3).

by regulations and government initiatives (see Table 3/1). Anecdotal experiences from Ghana, Nigeria and Myanmar have shown that even in rural areas, owners of batteries are aware of the scrap value of lead-acid batteries and commonly sell old batteries to local scrap dealers who channel the batteries towards larger traders or recyclers. In more mature markets the purchasing price of waste batteries is expressed as percentage of the London Metals Exchange (LME) price for lead and can go up to 40 %. This market-driven collection is a major reason for quite high recycling rates of lead-acid batteries that achieve well above 50 % globally (UNEP 2011). Limits to such market driven collection might exist in remote areas where transport efforts and costs exceed potential revenue from sale and recycling.

Table 3/1: Indicative market prices for lead, lead scrap and waste lead-acid batteries
Source: USGS (2018); Recycling Magazin 73/05 (2018)

Material	Market price	Scope of market price
Lead with 99.97% purity	2618 €/t	Average LME price 2017
Lead-scrap	1600 €/t	Gate-price in Germany on 11.04.2018
Waste lead-acid batteries	650 €/t	Gate-price in Germany on 11.04.2018

The recycling of lead-acid batteries involves the breaking of the batteries, the capture and separation of the electrolyte, lead-scrap and plastics and the further processing of all fractions into saleable products. A generic flowchart of the lead-acid battery recycling process is given in Figure 3/2. Full implementation of this flowchart is commonly done by companies that have own production lines for new lead-acid batteries and so have a demand for all recycling outputs. Such companies are not only located in industrialized nations, but also in many developing countries.

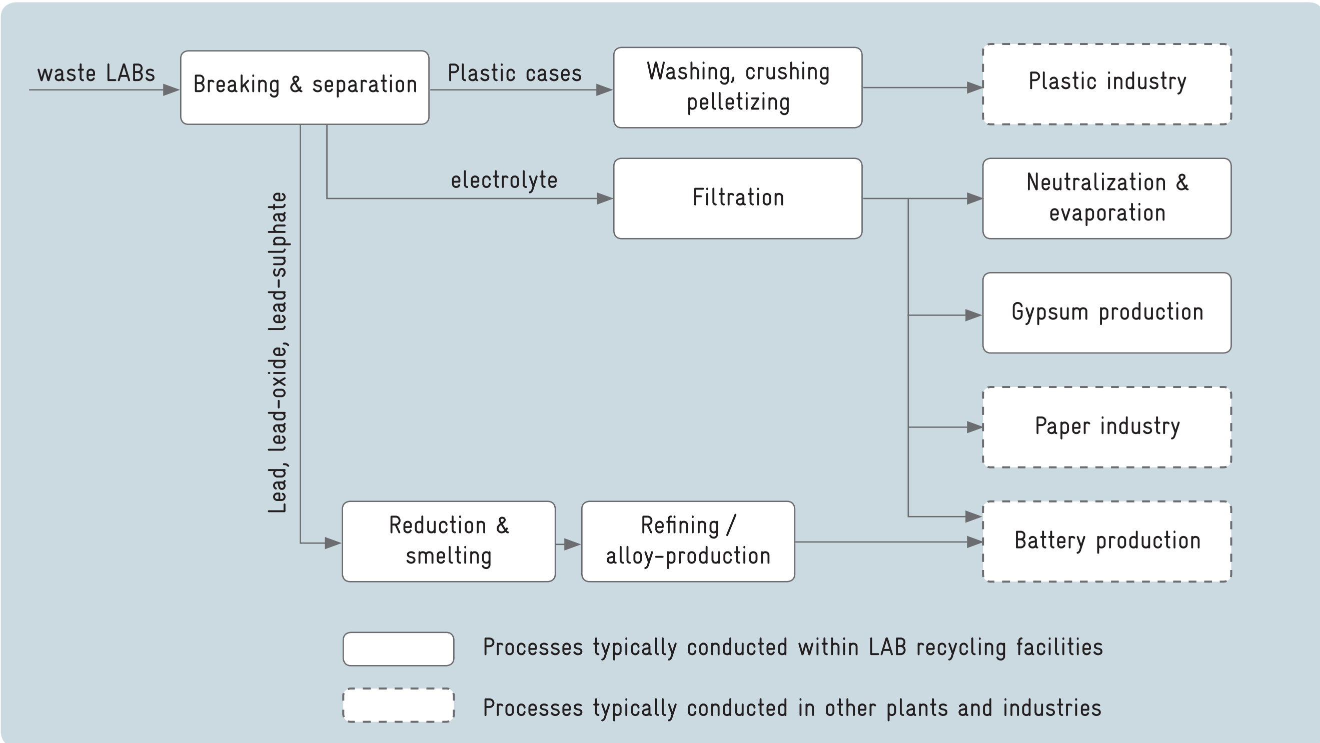
Recycling is done in all world regions and often by a broad variety of enterprises including informal small-scale recyclers, mid-scale plants and large scale recycling and smelting facilities (see Figure 3/3).

In particular small and mid-sized enterprises in developing countries and emerging economies often conduct only some of the process steps indicated in Figure 3/2. Such typical enterprise profiles are:

- Battery breakers that focus on the extraction of lead scrap to be sold to smelters;
- Artisanal lead smelters that produce crude lead to be sold to refineries;
- Mid-sized plants that recycle lead and plastics, but no electrolyte.

In addition, many developing countries have small repair and refurbishment industries for lead-acid batteries, mostly at the level of small workshops. These workshops usually repair or substitute anode or cathode material or faulty elements in automotive or industrial batteries.

Figure 3/2: Generic flowchart of lead-acid battery recycling Source: Öko-Institut e. V.



Waste lead-acid batteries, extracted lead scrap as well as lead from smelting and/or refining operations are commonly traded across borders. Here it is noteworthy that waste lead-acid batteries as well as lead scrap from battery breaking operations are classified as hazardous waste under the Basel Convention[5]. In contrast, lead ingots (crude and refined) do not fall under this definition and do not require notification according to the procedures of the Basel Convention when shipped across boundaries.

Despite various plants applying high environmental standards that effectively minimize emissions of lead and sulphur to the workplace and the environment, recycling of lead-acid batteries is known to be a severe environmental hot spot in many developing countries and emerging economies. Amongst others, unsound lead-acid battery recycling was classified as one of the world's worst polluting industries by the Swiss Green Cross and the US-American organization Pure Earth (Green Cross & Pure Earth 2016) and is known to have severe health impacts for many workers and communities next to recycling plants (Manhart et al. 2016).

5 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal.

Figure 3/3:
Impressions of various types of LAB recycling operations

A Refurbishing workshop
B Battery breaking facility
C Artisanal lead smelting
D Artisanal lead smelter
E Blast furnace of a sub-standard LAB recycling facility
F Rotary furnace of a modern LAB recycling facility

Typical health risks and emissions result from the following shortcomings:

› Uncontrolled drainage and disposal of battery acid (often already during collection);
› Sub-standard battery handling and breaking processes that cause emissions of lead particles and acid;
› Sub-standard smelting and refining processes with lacking or insufficient emission control;
› Uncontrolled disposal of hazardous furnace slags;
› Insufficient industrial hygiene and dangerous working conditions.

In this context it needs to be stressed that many of the applied sub-standard practices follow economic considerations: While many plants invest into processes and machinery to increase lead recovery, the implementation of environmental and health standards is in most cases associated with additional costs but with no direct effect on recycling rates and associated revenues. In environments where plant owners and managers are usually not held responsible for pollution and negative health effects, this is a clear motivation for sub-standard recycling. This problem is often aggravated by the fact that symptoms of lead poisoning are mostly unspecific and often resemble those of infectious diseases (fatigue, diarrhea, muscle pain…). Thus, worker drop-outs and illnesses in neighboring communities are sometimes falsely (and partly deliberately) allocated to non-industry causes.

Meanwhile the problems around lead-acid battery recycling have also been recognized on the international level and UN member states passed a related resolution on the third UN Environmental Assembly in December 2017 in Nairobi. Amongst others, this resolution encourages member states to "adequately address releases, emissions and exposures from waste lead-acid batteries, including recycling, and utilizing appropriate standards and criteria" (United Nations Environment Assembly 2017).

3.2 LI-ION BATTERIES

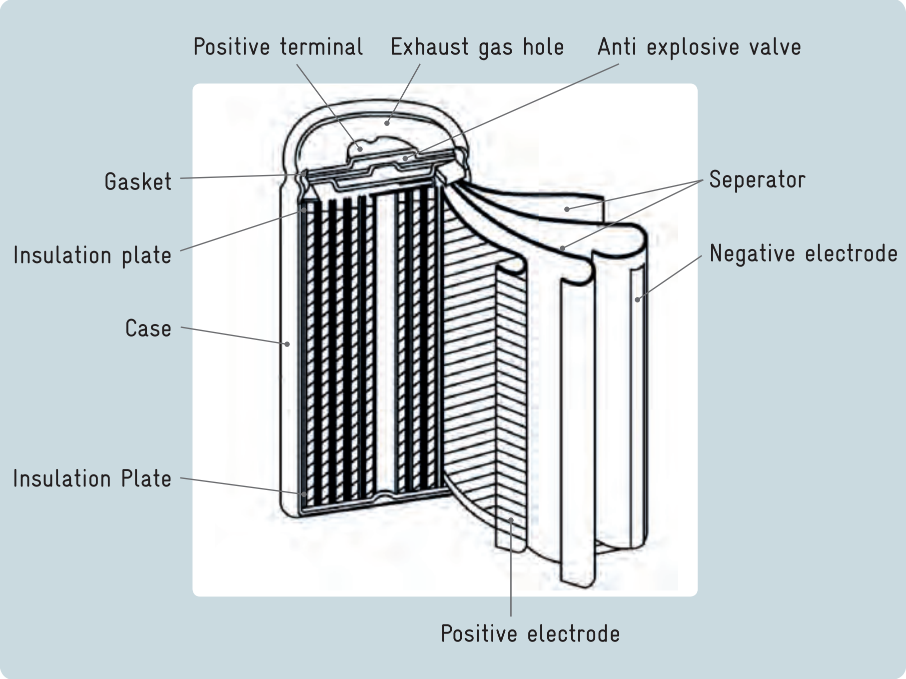
3.2.1 Types, prices & life-times

Li-ion batteries can be categorised in a number of different chemistries, with the following being the most relevant in today's economy:

› LNMC (lithium-nickel-manganese-cobalt-oxide)
› LCO (lithium-cobalt-oxide)
› LNCA (lithium-cobalt-aluminium-oxide)
› LMO (lithium-manganese-oxide)
› LFP (lithium-iron-phosphate)
› LTO (lithium-titanate)

The chemistries containing cobalt (LNMC, LCO and LNCA) have higher energy-densities compared to other Li-batteries but are also more expensive. They are therefore predominantly used in mobile applications such as smartphones and electric vehicles where weight and energy-density are of high relevance. Stationary applications mostly use the cheaper LMO or LFP batteries. Although LTO batteries have distinctive advantages in terms of fire safety (see section 3.2.2), they are not produced and used in large numbers due to low energy densities and are still quite expensive. Thus, the following analysis focuses on LMO and LFP, which are currently the only relevant Li-batteries for off-grid solar power projects.

Figure 3/4: Structure of a cyclindrical Lithium-ion battery cell Source: Panasonic 2007



In terms of battery life-times, both chemistries are usually more durable compared to lead-acid batteries with LFP having advantages over LMO. Prices differ significantly with LMO cells being roughly twice as expensive as LABs, and LFP twice as expensive as LMO (Manhart et al. 2018). Here it needs to be stressed that prices for Li-batteries change quickly and that on average, prices declined by around 20% per year over the last years (Curry 2017). In case this trend continues, the purchasing price of LMO batteries might be at the level of LABs in around 2020.

3.2.2 Toxicity potential & safety risks

Despite the absence of heavy metals in Li-ion batteries, there are various constituent parts with potentially negative effects on human health and ecosystems (Stahl et al. 2016). Despite the fact that the chemical composition of Li-ion batteries may vary significantly between different types and sub-types, it needs to be assumed that all types concern substances with potentially hazardous effects.

While toxicity potential of LMO and LFP batteries are significantly lower compared to those of LABs, it needs to be considered that LABs commonly find their way to recycling facilities. In contrast, LMO and LFP batteries have little recycling value and are therefore quite unattractive for local and global recycling markets. As a result, they are more likely to be disposed of in an uncontrolled manner (see section 3.2.3).

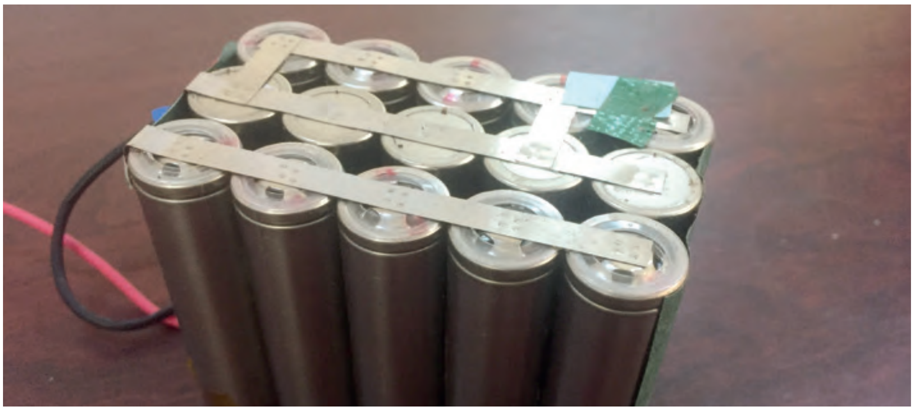
Apart from their toxicity potential, the use of Li-ion batteries is under certain conditions associated with safety risks. The following passage on related risks is taken from (Manhart et al. 2018).

Overcharging, high temperatures and physical stress to battery cells can cause so-called thermal runaway, which commonly leads to the destruction of the battery, fire and even explosions. In addition deep discharging can also cause battery fires. These processes are shortly described in the following:

- Overcharging and high temperatures can lead to the decay of the cathode material, which is a strongly exothermic reaction. The increasing temperature causes the organic electrolyte to evaporate, which leads to the formation of flammable gases. Deep discharging can also cause the evaporation of the organic electrolyte and the formation of flammable gases. In such a case, thermal runaway might start when a cell is charged: Due to the absence of electrolyte, the charging power is converted into heat, which can cause the decay of the cathode material and ignition of the contained gases (Mähliß 2012).
- Due to manufacturing errors (e.g. small accumulation of microscopic metallic particles, uneven separators), individual cells might be subject to short-circuiting, overheating and the chemical and physical processes described above. While most manufacturers have very stringent quality controls to reduce such risks as much as possible, it must be assumed that less recognized manufacturers (e.g. producing for very price sensitive markets) have less stringent controls (Battery University 2018).

Generally, overcharging, deep discharging and physical stress do not necessarily lead to a thermal runaway. But improper handling, exposure to high temperatures and physical stress can affect battery cells negatively, which can subsequently cause a thermal runaway even days and weeks after individual stress-peaks.

One problem of a thermal runaway is the risk of ignition of other neighbouring cells. Most battery packs contain several cells and the heat of one burning cell can easily trigger thermal runaways in neighbouring cells (see image below).



Typical arrangement of Li-ion cells for a battery pack used in SHS
© Öko-Institut e.V.

There is an intensive debate on differences in fire safety of different types of Li-ion batteries. These debates usually refer to the following aspects:

› The decay of some cathode materials leads to the formation of oxygen, which fuels the battery fire from the inside. Thus, the cathode fire cannot be extinguished. This aspect applies to cobalt containing Li-ion batteries and therefore has no relevance for LMO and LFP.
› Most cathode materials used in Li-ion batteries decay at temperatures between 180° C to 225° C (Hietaniemi 2015). The cathode material of LFP-batteries is thermally more stable and can resist temperatures of up-to 300°C (Kurzweil & Dietlmeier 2016).

For these reasons, LFP batteries are commonly referred to as those Li-ion batteries with the lowest fire risks. Nevertheless, other experts argue that differences are negligible and that all types of Li-ion batteries are associated with fire risks (EnBausa.de 2014).

As overcharging and deep discharging are major factors that can trigger thermal runaways, it is obvious that batteries used in energy access projects need to be equipped with suitable charge controllers. Here it needs to be stressed that changes to systems might also be done during the use phase so that the existence of a charge controller cannot entirely rule-out the above mentioned risks. In particular with SHS it was observed that users commonly bridge the charge controller in order to extend the period of power supply (Manhart et al. 2018). This is commonly done in relation to TV-consumption (e.g. watching sport events).

3.2.3. Recycling practices & infrastructure

Recycling of Li-ion batteries is a rather new field and currently only done by a few plants such as Umicore (Belgium), Retriev Texchnology (USA), American Manganese (Canada), Accurec (Germany) and Redux Recycling (Germany) (Harvey 2017; Recycling Magazin 73/06). The plant with the biggest recycling capacity is Umicore's facility in Hoboken, Belgium, which can recycle up to 7,000 t of batteries per year, which is equivalent to 250,000,000 mobile phone batteries, or 35,000 batteries from electric vehicles. It focuses on the recovery of nickel, copper, cobalt and rare earth elements from NiMH and Li-ion batteries. Lithium can be recovered from the slag phase (Umicore 2018). Other battery materials such as iron, graphite, phosphor and organic compounds are lost in the process. According to (Weyhe 2013), other recycling processes focus on recovering similar materials. From an economic perspective, the presence and concentrations of cobalt and nickel are main factors influencing the total profitability of Li-ion battery recycling.

LMO and LFP batteries do not contain nickel, cobalt and rare earths. Concentrations of lithium are around 1%, while copper concentration lies between 7% and 8% in LFP batteries (Stahl et al. 2016). It is assumed that LMO batteries have similar lithium and copper contents.

Thus, less than 10% of LMO and LFP batteries can be recycled in the established processes. This situation is further aggravated by the fact that recycling of lithium is – from an economic perspective – only a by-product of the recycling of other materials and economically not significantly more attractive than primary production. Thus, recycling of LMO and LFP batteries is associated with net-costs (Batteries International; Weyhe 2013).

For recycling, end-of-life Li-ion batteries need to be collected and shipped to appropriate treatment facilities, such as one of the above mentioned plants. Collection and shipment are subject to additional costs and challenges, mainly linked to the necessity to comply with international regulations on the transport of dangerous goods. These challenges mostly relate to potential thermal runaways of waste batteries (also see section 3.2.2). As laid-out by (Manhart et al. 2018) Li-ion batteries with a residual charge of at least 30% can be subject to thermal runaway. As battery recycling relies on the accumulation and management of larger battery volumes, the thermal runaway of one cell can ignite other cells and cause larger battery fires damaging entire storage and recycling facilities, which has already happened in various places worldwide. Over the last years, various strategies have been developed to avoid such chain reactions in recycling facilities and during bulk transports. Often, several of the following strategies are applied in parallel:

- Manual discharge of batteries. A full discharge of all cells can effectively minimize fire risks, but is also associated with labour costs. Discharging devices and processes need to make sure that workers are not subjected to electrical shocks.
- Prolonged storage (several weeks) to make use of self-discharge effects prior to transports.
- Storage in buckets/drums that are places in some distance from each other so that a fire in one bucket cannot ignite batteries in other buckets. This strategy is commonly applied in combination with embedding in sand (next point).
- Storage and transport of Li-ion batteries embedded in sand (in buckets or drums). In case of a thermal runaway, the developed heat is absorbed by the surrounding sand and produces a glass-like enclosure around the battery. This type of packaging is widely established as the main means for international trans ports but also requires additional safeguards (e.g. to avoid a built-up of pressure in drums from thermal runaways).
- Permanent monitoring of temperatures in storage drums. In case of temperature increases, fire-fighting measures are taken immediately.

Further risks exist when Li-ion batteries with residual charge are falsely treated as lead-acid batteries. In particular when batteries are broken manually, fires and explosions can seriously harm workers of such facilities.

In developing countries and emerging economies, collection and recycling (export to recycling facilities) of Li-ion batteries is still in its infancy. With positive market values for cobalt-containing batteries ranging between 200 and 2,500 €/t (Manhart et al. 2018), it is likely that collection efforts for such batteries will gain momentum, in particular in larger urban centres and after solving the challenges related to transport logistics. But due to the negative net-value of LMO and LFP batteries that can cause net-costs as high as 2,500 – 3,500 €/t (Magalini et al. 2017), these types will most likely not be collected and managed in such systems. In case there are no collection and treatment efforts financed by other means than raw material recovery, these batteries will most likely not undergo any specific collection and treatment and will be managed in parallel with mixed municipal solid waste (disposal, open burning etc.).

Discharging and embedding in sand are some of the strategies used to reduce risks from thermal runaways during transport of Li-ion batteries
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4 / BUSINESS MODELS AND THEIR IMPLICATIONS ON END-OF-LIFE MANAGEMENT

The solar power industry in developing countries and emerging economies has proven to be very flexible as it has had to overcome various difficulties related to marketing of products and systems with high upfront costs (e.g. SHS) and is in direct competition with other partly subsidized energy options (e.g. kerosene). Usually two main business models are applied:

1. Models where the appliance is purchased. This includes direct cash purchases or sales "assisted" either by financing institutions or through access to credit mechanisms. This business model is typically applied for smaller systems such as solar lanterns and small solar home systems, which often represent the entry point on the energy ladder.
2. Models where the appliance is leased or the ownership is progressively transferred after a period of time (lease-to-own). Customers are assisted with the upfront capital costs and get maintenance and after-sales service during their repayment periods, which are normally for a period of three years or more. Systems are usually equipped with a mechanism that allows providers to remotely disable a system when payment is overdue. These models have been applied in institutional microfinance-based programs such as those in Bangladesh and India, as well as in recent years through plug and play systems provided by private companies linked with repayments using mobile money, in so-called "pay-as-you-go" (PAYG) models. These newer PAYG models have seen major growth in Eastern Africa, where mobile money payments are more widely used (GOGLA 2017).

Leasing or PAYG models used for SHS create stronger and more stable relationships with the customers, at least until the ownership of the product is finally transferred to the consumer. In this context, PAYG models offer an opportunity to better integrate take back programs and operations, particularly in the case of consumers that are moving to newer products at the end of the pay-back period. In addition, during maintenance and warranty periods, the companies have access to faulty products and components, including batteries, which are channeled to their warehouses. This offers a good opportunity to integrate pick-up service for battery waste and e-waste in more remote areas. Beyond PAYG, the off-grid solar sector has developed a wide variety of sales and distribution options such as retail shops and kiosks, local agents, NGOs and partnerships with mobile phone operators. It is estimated that up to 50% of sales come from such distribution partnerships and not from traditional sales and distribution models (GOGLA 2017).

These new distribution models with stronger customer relationships can help, at least partially, to overcome the typical difficulties of structuring a collection and recycling system for waste batteries and e-waste in the context of developing countries. This includes aspects such as access to waste, awareness raising on consequences of improper management, development of hand-over incentives and logistics provision to collect from rural areas. The distribution of batteries and equipment to rural areas creates logistical challenges and cost implications for sound collection and recycling at the end-of-life. Apart from this, the following issues have to be considered:

- In all cases the willingness of consumers (or waste holders) to give away obsolete batteries and e-waste to avoid improper disposal is fundamental and cannot be by-passed. It might therefore be required to create some forms of incentives (monetary or none-monetary) for waste holders to hand-in old batteries or defined e-waste types.
- The role of local repair and refurbishment activities, especially for SHS components, and connected appliances need to be factored in: The availability of spare parts from discarded appliances creates an economic incentive for the waste holder to sell appliances and batteries to a local repair industry instead of returning them for recycling purposes. While there are already developed repair and refurbishing industries for lead-acid batteries in many developing countries (see section 3.1.3), it is also likely that comparable industries will develop for Li-ion batteries once sufficient end-of-life volumes are available. Here it needs to be stressed that refurbishing of lead-acid batteries should be completely discouraged as related processes almost inevitably cause emissions of lead to the workplace and the surrounding environment. For Li-ion batteries, reuse (e.g. of cells) will again raise the question of potential thermal runaways in new applications (see section 3.2.2).
- Some companies are trying to proactively develop take-back operations on a voluntary basis. However, the cost of proper take-back and recycling were not included in the initial pricing structure of the product or PAYG model. This is particularly problematic for systems using battery types and components with a negative net-value (e.g. LMO and LFP batteries).

Unloading an SHS delivery
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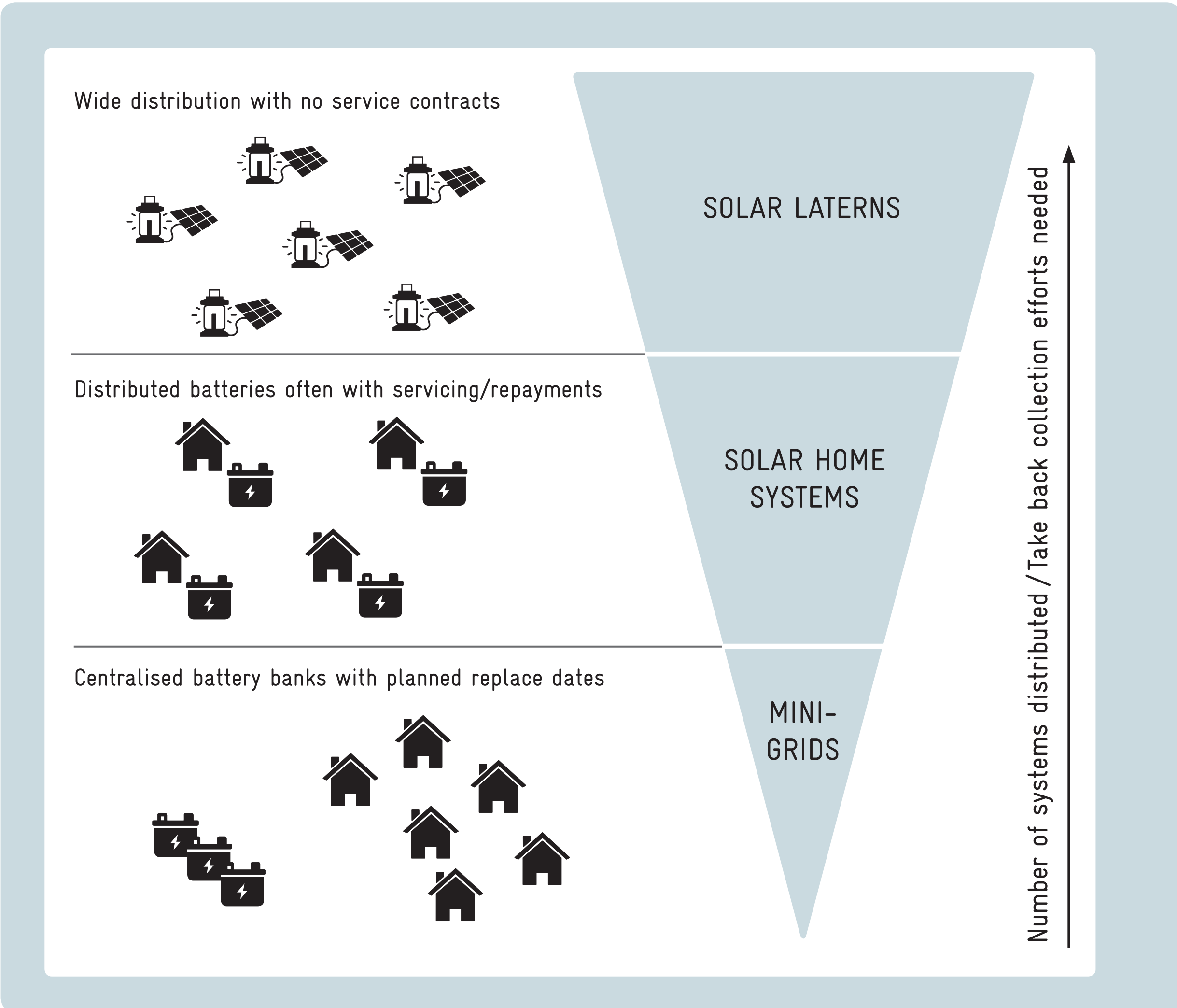
In some cases, innovative collection systems have been planned or piloted: Amongst others in Kenya, TOTAL tested the use of petrol stations as drop-off points for solar waste, thus leveraging on existing and easily accessible infrastructure to be used as collection points. Other companies have considered using "road shows" usually organized to facilitate distribution of products for waste related awareness raising and collection.

Solar lanterns have the largest sales volumes worldwide, and also represent the most challenging devices from a take-back perspective, since they have a net recycling cost, and are geographically widely distributed. While these devices tend to offset some e-waste effects from dry cell batteries used in torches, they still generate e-waste after their 3 – 4 year lifetime (IFC 2018). In some regions also mini-grids have been deployed to provide energy solutions to off-grid communities. Compared with SHS and solar lanterns, these systems have the logistical advantage of centralizing large numbers of batteries, panels and other components in one place. Furthermore, planning can also be made for exchanging batteries from centralized battery banks at a foreseeable date in the future. In these cases the mini-grid provider should ensure that an appropriate recycling solution is found for these batteries when this exchange date comes. Figure 4/1 shows the various impacts that different solar technologies have on the efforts needed for reverse logistics.

Figure 4/1: Impact of business model on the logistics for waste collection Source: Own figure



5/ OPTIONS FOR ENERGY-ACCESS PROJECTS

This chapter aims at giving recommendations and directions to project managers and practitioners involved in publicly or privately funded attempts to broaden access to electricity in off-grid areas of developing countries and emerging economies (here referred to as 'energy-access projects'). Generally, there is an increasing consensus that energy-access projects and solar power companies can and should consider the above described issues around end-of-life management in their activities and try to implement strategies to mitigate negative effects while proactively contributing to sustainable solutions in this field. This viewpoint is mainly based on extended producer responsibility (EPR), which represents a globally accepted concept for products and waste streams posing significant risks to human health and the environment. In a nutshell, this concept says that economic operators placing such products onto the market carry responsibility for the sound end-of-life management of an equivalent amount of waste of such products. While in most developing countries there is no legal obligation covering this responsibility, it can also be regarded as ethical element for businesses that sell and distribute solar power equipment and accessories in developing countries and emerging economies. Already in 2014 the Global Off-Grid Lighting Association committed to have the Extended Producer Responsibility (EPR) principle as cornerstone for activities of their members (GOGLA 2014). At the same time, more and more investors of the solar power industry demand convincing strategies to address so far unresolved waste issues in business plans and implementation. Where public authorities or development cooperation institutions support the purchase of solar power equipment, they also have a responsibility to make sure that negative impacts from this equipment are avoided from a sustainability perspective.

The following sections aim at supporting strategy development and decision making in this field and present various ways how this responsibility can be translated into practice. In most cases, the options presented below should be bundled and implemented in a coherent package.

5.1/Choosing battery types

Practitioners working in energy-access projects are often involved directly or indirectly in procuring components and delivering these to their sites of use. The choice of battery types is an important project decision and end-of-life management should already be considered in such initial project phases. Chapter 3 indicates that – despite their various differences – neither Li-ion batteries, nor lead-acid batteries are clearly superior in terms of end-of-life management as both battery types have characteristics that might lead to negative environmental impacts and/or health and safety risks during use-phase, recycling and disposal. A comparative overview on these characteristics is given in Table 5/1.

Table 5/1: Comparison of battery characteristics relevant for end-of-life management strategies
Source: Own compilation based on the analysis of sections 3.1 and 3.2.

	LEAD-ACID BATTERIES		LITHIUM-ION BATTERIES	
	Automotive LAB	Deep-cycle LAB	LMO	LFP
Purchasing price	very low	low	medium-high	high
Expected life-time	very low	medium	high	high – very high
Safety risk in use-phase	low	low	medium/high[1]	medium/high[1]
Toxicity potential	very high	very high	medium	medium
Recyclability	very high	very high	medium	medium
Profitability of recycling	high[2]	high[2]	very low[3]	very low[3]

[1] Medium in mini-grids, high in SHS [2] Net revenues [3] Net costs

Nevertheless, on a project level, the choice for or against certain battery types is a main decision that affects all other project strategies related to battery end-of-life management. Although it is understandable that managers of energy access projects would like to have clear recommendations for or against certain battery types, such guidance cannot be given on a generic level. This is because battery related decisions also need to take into account other criteria such as availability and suitability for the intended use. Furthermore, end-of-life management and recycling infrastructure vary from country to country and case-to-case: While some countries have no developed legal framework or sound battery recycling infrastructure at all, others are further developed in this regard. As illustrated in chapter 4, also the project set-up and involved business models can play a significant role. Depending on these framework situations, one battery type might make more sense than another. The decision-making process in this field can be complex, but the following (fictional) examples might serve as first starting points:

EXAMPLE 1
(no sound recycling infrastructure):

Starting point on a *country* level:

No developed formal e-waste and battery collection and recycling. E-waste is mostly handled by informal sector players that focus on valuable materials such as copper and aluminium. The related recycling processes are crude. There are few formal recycling companies that offer sound recycling of e-waste, in particular for businesses. There is one industrial lead smelter that focuses on the recycling of waste lead-acid batteries. The company recycles most end-of-life LABs of the country but is known to be highly polluting. The management is unwilling to improve recycling processes. The export of waste lead-acid batteries is restricted by law[6].

6 Various countries have export restrictions on certain scrap types as a means to protect local recycling and manufacturing industries.

EXAMPLE 1
(continuation):

Starting point on a *project* level:

The project supports the establishment of mini-grids in rural areas. Mini-grid equipment ownership is transferred to community organizations. Equipment maintenance is done by trained local engineers.

Battery choice:

From a project perspective, this situation favours the use of Li-ion batteries as there seems to be little chance to identify a sound solution for waste lead-acid batteries. In this context, the pollution risks from Li-ion batteries appear to be lower. At the same time, Li-ion batteries are not used at household level and equipment management is done by trained staff, which should widely mitigate safety risks. The project should consider partnering with a local responsible recycling company to develop a plan for battery and e-waste collection.

In case lead-acid batteries are used in such a setting (e.g. for availability reasons), the project should consider awareness raising campaigns and training efforts for environmental authorities. The goal of such measures should be an increased regulatory pressure on the existing lead recycling industry to improve operations (also see section 5.3 and 5.4).

EXAMPLE 2
(recycling option for lead-acid batteries exists)

Starting point on a *country* level:

No developed formal e-waste and battery collection and recycling. E-waste is mostly handled by informal sector players that focus on valuable materials such as copper and aluminium. Informal recyclers also collect waste lead-acid batteries all across the country. The batteries are sold to a local company that needs the lead, plastics and acid for the production of new batteries. As this facility also has a demand for sulfuric acid, the system encourages the collection of wet batteries (with acid). Thus, uncontrolled acid drainage is uncommon. The applied recycling processes in this facility have undergone a qualified independent audit and can be considered to be environmentally sound.

Starting point on a *project* level:

The project supports the distribution of solar home systems in rural areas. Due to low acceptance, business models such as pay-as-you-go are not applied. Thus, the equipment ownership is transferred to the users with the day of installation. Service and repairs are done by numerous local businesses that evolved over time and that have no tight connection to the project and its partners.

Battery choice:

In this situation, deep-cycle lead-acid batteries seem to be preferable over Li-ion batteries. This is because the project and its partners have very limited control over end-of-life batteries and cannot guarantee sound collection. In turn, there is already a market driven collection for waste lead-acid batteries in combination with a sound recycling facility. In addition, the use on a household level (solar home systems) requires ambitious safety standards. Although such standards can also be fulfilled with Li-ion batteries, lead-acid batteries are an established technology with very limited safety risks in the use phase.

In case Li-ion batteries are used in such a setting (e.g. durability reasons), the batteries and the charge controller should be encased in a common housing as an effective barrier to user manipulations (see section 3.2.2). Furthermore, it should be considered to introduce a collection system for batteries (and probably also other e-waste types), even if this is associated with additional costs. The goal of this measure should be to channel at least an equivalent amount of batteries and e-waste to sound recycling.

The availability of a locally available and audited recycling process for the lead-acid batteries is an important factor for the battery choice in this case – feasibility scoping should assure that the audited facility is legitimate and operates in an environmentally sound manner. Where this is not the case, but where a local recycler is already quite close to international standards, the project may consider steps to assist this recycler in undertaking an audit and implementing necessary improvement steps to reach sound recycling processes[7].

RECOMMENDATION SUMMARY:

- Consideration on the battery types to be used in a project should already consider end-of-life management options and implications.
- From end-of-life perspective, a general recommendation for or against a certain battery type cannot be given. Related decisions therefore need careful prior evaluation of local recycling and disposal options.

7 Here it needs to be stressed that many sub-standard processes are in a condition where upgrading requires a fundamental change of the applied business model and will require multi-million investments in new equipment and remediation of the contaminated site. In such cases, this co-operative approach will most likely not yield satisfactory results and will require efforts from regulatory authorities (enforcing binding minimum standards).

5.2 PRODUCT & SYSTEM DESIGN

A major means to reduce environmental impacts from hardware of energy access projects is product and system design. Setting quality and durability requirements that enable long battery and system life-times effectively reduces the amount of generated waste batteries and e-waste. At the same time, battery and system designs can help to reduce safety risks related to potential thermal runaways of batteries (see section 3.2.2). While product designs can also reduce the amount of hazardous substances in products, this aspect is not elaborated in more detail in this report. This is because the battery choice as described in section 5.1 has by far the largest impact on hazardous materials in batteries and should be prioritized first. Compared to this, battery specific material compositions have a comparably low impact.

A common means of ensuring long life-times and safe use conditions is the use of defined quality standards for systems and individual components. The following table gives an indicative overview on related standards.

Generally, it is advised to combine ambitious requirements for systems with specific quality requirements for the battery type(s) used. One constraint might be the fact that many life cycle test methods for batteries are very time consuming, which might cause delays for projects and system distribution. In case such time consuming tests are considered to be unfeasible, batteries should at least fulfil the quality requirements of Lighting Global. Tests should be conducted according to the methods defined in the Solar Home System Kit Quality Standards or in IEC 62257-9-5.

System design choices can influence durability and product lifetime

For Li-ion batteries used in SHS, it is also recommended to additionally apply a system design where charge controller and battery are encased in one common housing that cannot be opened with standard tools such as screwdrivers. Appropriate warning signs should discourage any manipulation of the battery and the charge controller and should indicate associated risks such as electric shocks, fires and explosions. In addition, it is recommended that the type and chemistry of all batteries (e.g. LFP, LMO) are indicated on the housing.

Table 5/2: Overview on system and battery related standard documents (non-exhaustive) Source: Own compilation

Solar Home System Kit Quality Standards by Lighting Global	Requirements for SHS on a system level
IEC 62257-9-5: Recommendations for renewable energy and hybrid systems for rural electrification – Part 9-5: Integrated systems - Laboratory evaluation of stand-alone renewable energy products for rural electrification	Testing provisions for SHS on a system level.
IEC 61427-1: Secondary cells and batteries for renewable energy storage – General requirements and methods of test – Part 1: Photovoltaic off-grid application.	Requirements and performance test methods for all types of secondary batteries. This norm refers to a number of (battery) chemistry-specific IEC norms (see below for exemplary selection).
IEC 60896-11: Stationary lead-acid batteries – Part 11: Vented types - General requirements and methods of test	Specific requirements & testing provisions for stationary vented LABs.*
IEC 60896-21: Stationary lead-acid batteries – Part 21: Valve regulated types – Methods of test.	Specific testing provisions for stationary valve-regulated LABs.
IEC 61056-1: General purpose lead-acid batteries (valve-regulated types) – Part 1: General requirements, functional characteristics – Methods of test.Specific requirements & testing provisions for general purpose valve-regulated LABs.IEC 61960: Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for portable applications.	Specific requirements & testing provisions for portable lithium cells and batteries.
IEC 62620: Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for use in industrial applications	Specific requirements & testing provisions for industrial lithium cells and batteries.

* According to Lighting Global, batteries used in SHS can either be portable or stationary ones, depending on the size of the system. The specific standard(s) should be chosen accordingly.

RECOMMENDATION SUMMARY:

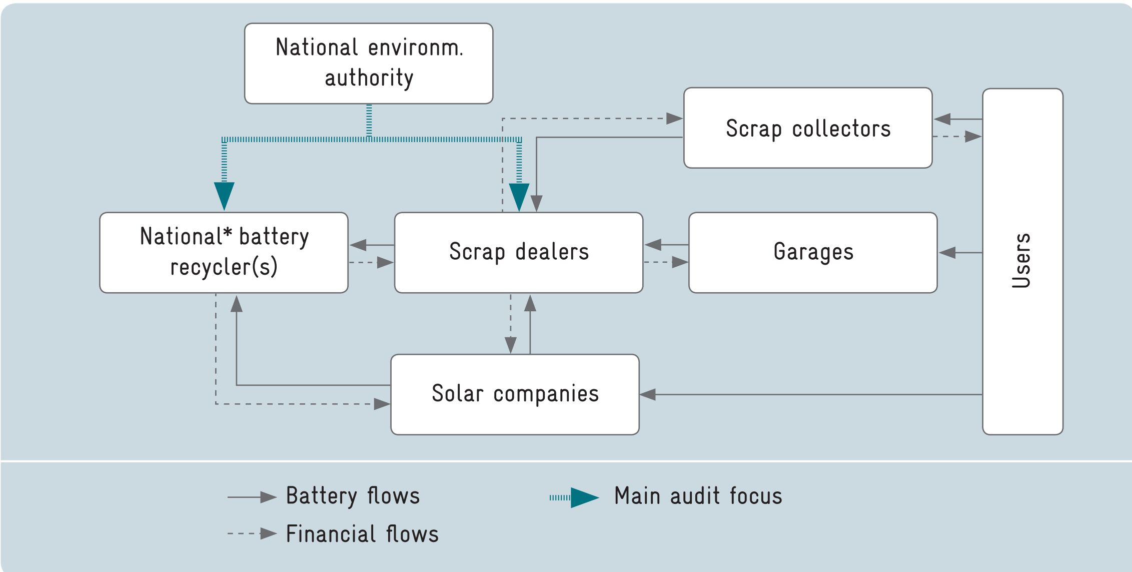
- Batteries and systems should be designed for long life-times
- Related attempts can be supported by various quality standards for systems and batteries
- When Li-ion batteries are used on a household level (solar home systems), system design should discourage any manipulation to the battery unit and the charge controller

5.3 PARTNERSHIPS & BUSINESS MODELS

Partnerships and business models are decisive for developing a collection system and recycling solutions for waste batteries and also for other types of waste from solar power installation. The following points highlight aspects that should be considered by energy access projects and solar power companies when developing strategies for sound end-of-life management:

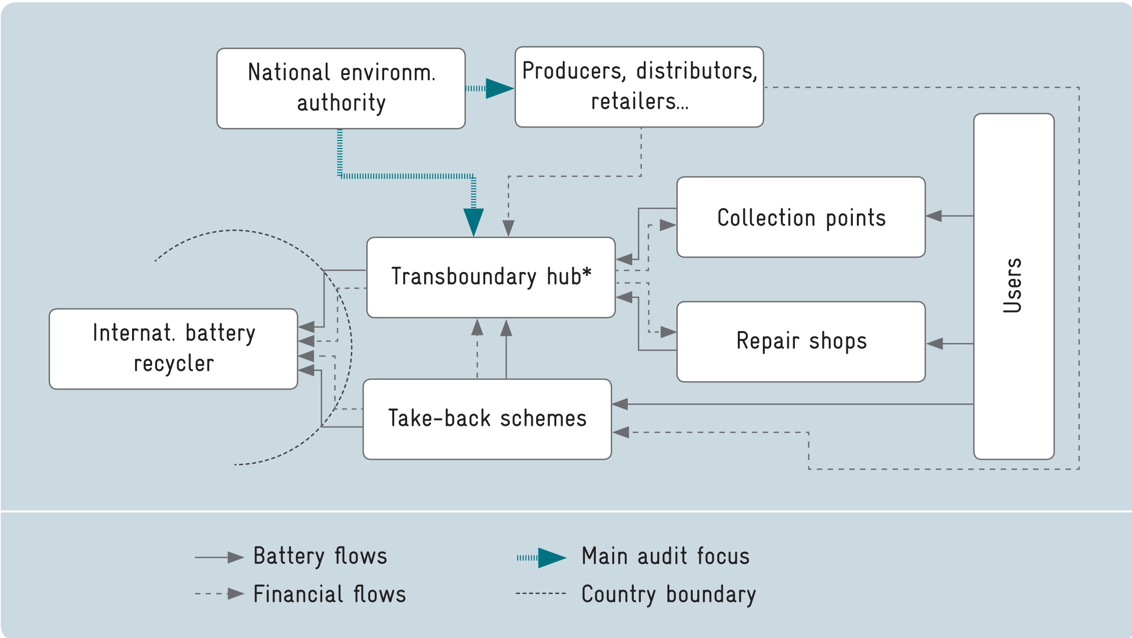
- As indicated in section 3.1, lead-acid batteries are already collected and recycled in many world regions because of their high, intrinsic economic value, which is relatively easy to exploit, also with rudimental and polluting recycling processes. In case a company mainly uses lead-acid batteries in its products, it should be considered to primarily focus efforts on improving the existing collection and recycling system rather than building-up parallel collection infrastructure. A generic model management chain for waste lead-acid batteries is given in Figure 5/1. Energy access projects may support improvements by working with solar power companies to build-up sound collection and by supporting national environmental authorities (also see section 5.4).
- In contrast, LMO and LFP batteries will not be collected based on existing market incentives because of their negative economic value (see section 3.2).

Figure 5/1: Generic management chain for waste lead-acid batteries in developing countries Source: Own figure



* Where appropriate local recycling facilities do not exist, export of lead-acid batteries to international recyclers may be necessary.

Figure 5/2: Generic EPR based management chain for waste Li-ion batteries in developing countries
Source: Own figure



* A transboundary hub may be any organization collecting and exporting Li-ion batteries to international recyclers

Thus, collection and recycling of such batteries will most likely require additional efforts that will be associated with additional costs. A generic management chain is given in Figure 5/2. Here it needs to be noted that this chain represents one possible future option for managing waste Li-ion batteries in developing countries.

› As indicated in chapter 4 companies following business models that create strong and stable relationships with customers (PAYG) have some practical advantages for developing own collection systems. This is because they keep a stronger link with their existing customers so that they can use their service and repair personnel and infrastructure to collect obsolete equipment. For companies relying on external service support for customers, partnerships with such service providers might yield comparable results.
› While some company initiatives try to focus collection on their own brand equipment, it should also be considered to accept waste batteries from other brands and sources. In general, such open collection efforts are considered to be more efficient and more likely to channel back significant waste volumes as volume is a key driver behind any waste management system.
› As a general rule, a collection system should have a kind of volume-based target. Company based benchmarks should be derived from the amount of batteries and equipment brought onto the market in a defined time period or based on estimations of the waste being generated in the country.

- In situations where good-willed companies are competing with an informal e-waste or lead-acid battery recycling chain, often a large volume of batteries are needed to make environmentally sound lead recycling viable. To achieve volumes, as well as to reduce costs, projects and companies might consider joining forces with other market players of the solar industry as well as with other industries bringing batteries into the market (e.g. automotive industry, mobile network providers). In many countries with mandatory EPR systems, companies established so-called Producer *Responsibility Organizations* (PROs) to jointly organize collection, recycling and a fair distribution of costs.
- Apart from collection, it is of vital importance to identify sound recycling and disposal options for the collected batteries. While local recycling solutions should generally preferred, their environmental and health and safety related performance needs to be assessed carefully. This is particularly relevant for recyclers of lead-acid batteries, which should not be chosen without an independent environmental and health and safety assessment of all involved process steps. In case there is no suitable recycling partner within the country, the export of full batteries (including the acid) should be considered[8].
- For Li-ion batteries recycling most likely requires exports to specialized plants (see section 3.2.3 and Figure 5/2). Thus, sound management requires partnership with an experienced waste management and/or logistics company. In case no local company can be identified for this task, exports might also be organized via an international service provider such as *Simpli Return*.

RECOMMENDATION SUMMARY:

- Projects using lead-acid batteries should focus on improving existing recycling infrastructure and processes. In this context, links to the policy level should be explored (see section 5.4).
- In the case that no suitable local management option for waste lead-acid batteries is in sight, exports to sound facilities should be considered.
- Projects using Li-ion batteries should focus on piloting collection and recycling solutions.
- For collecting, synergies with distribution and maintenance networks can help to reduce efforts and costs.
- Efforts and costs may also be minimized by co-operations with other projects and companies placing batteries onto the market.
- Collection schemes should work with volume based targets.
- In any case, projects should be aware that collection and sound recycling of Li-ion (LMO and LFP types) is associated with net costs.

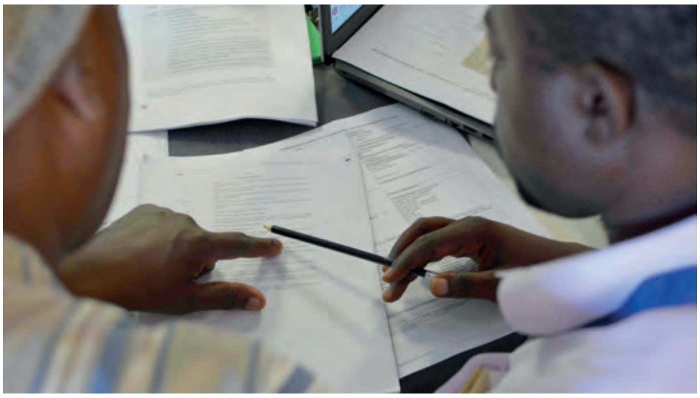
8
Guidelines on how to organize such exports can be downloaded here (Versions in French, Spanish, Arabic, Hausa and Twi are available on request):
http://www.econet.international/fileadmin/user_upload/poster_lab_en_A3-A4.jpg

5.4 POLICY

Energy access projects and solar power companies can also engage and support the development of policies for sound management of battery waste and e-waste in their countries of activities. In particular energy access projects with close government relationships might have considerable possibilities to support positive change in this field.

As already indicated in the beginning of this chapter, policies for waste batteries and e-waste should be based on the principle of extended producer responsibility (EPR). While there is a wide range of potential EPR implementation models, most of them can be classified in two main types:

- EPR models where producers and importers are required to collect and recycle defined waste volumes (either individually or via a producer responsibility organization) retaining both financial and operational responsibility;
- EPR models where producers and importers have to pay into a central fund destined to finance sound collection and recycling, thus only retaining financial responsibility without having any control over operations.



Policy plays an important supporting role for end of life management
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While both of the above listed models have strengths and weaknesses, the development of all mandatory EPR models require a sound policy framework, including laws and regulations that specify how economic operators that place equipment onto the market are held responsible for waste managing issues. Typically, such policy development is a lengthy process that will not yield tangible results in the short-term. Nevertheless, energy access projects and solar power companies can stimulate and enrich related developments by frontrunner initiatives such as those described in section 5.3.

Regarding the management of waste lead-acid batteries, energy access projects and solar power companies can also do policy support on a lower intervention level, and possibly also in combination with own attempts to identify suitable recycling partners. This can be done by conducting a combination of awareness raising and training activities on this important subject. One entry point can be the recent UNEA resolution that clearly encourages UN member states to take action in this filed (United Nations Environment Assembly 2017). Such an initiative might be composed of the following elements:

- Initial awareness raising for decision-makers in policy, regulatory authorities, recycling industry and battery-using industry (solar industry, mobile network operators, automotive industry);
- Mapping of national lead recycling industry;
- Training of auditors / regulatory authorities for environment, labour and health & safety to enable them to conduct full qualified audits in their domestic lead recycling industry;
- Benchmark audits of all lead-acid battery recycling facilities of a country (in close co-operation with regulatory authorities).
- Definition of improvement plans (in close co-operation with regulatory authorities).

These activities were successfully conducted by the Sustainable Recycling Industries Programme (SRI) in Ghana (see image below) and led to mandatory plant specific improvement plans that are tied to the factories' operating licenses: In case a plant does not implement the plan as outlined, it will be sanctioned by the regulatory bodies, which can encompass fines and temporary or permanent shut-down of operations.

This type of intervention does in most countries not require new laws or regulations as it can be based on general environmental regulations providing principles and emission limits for industry activities. In addition, this type of intervention is of high importance to achieve systematic improvements on a national level as sub-standard lead-acid battery recycling has economic advantages over high-standard recycling processes (see section 3.1.3). Thus, stringent enforcement of standards is a key element to improve lead-acid battery recycling anywhere in the world.

Benchmark audit in a lead-acid battery recycling plant in Ghana
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RECOMMENDATION SUMMARY:

- Energy access projects and solar power companies should support the development of policies for sound management of battery waste and e-waste in their countries of activities. Related policies should follow the principle of Extended Producer Responsibility.
- Policy development can be supported by leading by positive example. This may entail developing and implementing of sound collection and recycling solutions on a voluntary basis (also see section 5.3).
- Regarding the management of waste lead-acid batteries, awareness raising and training activities for authorities, recyclers and other industry players can help increase national standards for lead recycling industries.

Looking ahead, waste management will become increasingly important: Lighting Global forecasts off-grid solar market sales of 240 million units from 2017–2022 (IFC 2018)
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