tumi
E-Bus Mission

Measures Catalogue for Improving the Circularity of Batteries Used in E-Buses

Federal Ministry for Economic Cooperation and Development

C40 CITIES

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

icct THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

ICLEI Local Governments for Sustainability

ITDP Institute for Transportation & Development Policy

UITP ADVANCING PUBLIC TRANSPORT

WORLD RESOURCES INSTITUTE

ACKNOWLEDGMENTS

AUTHORS

Andreas Manhart	Oeko-Institut e.V.
Frederick Adjei	Oeko-Institut e.V.
Viviana Hernández López	Oeko-Institut e.V.
Yifaat Baron	Oeko-Institut e.V.

REVIEWERS

Alexander Batteiger	Go Circular Project GIZ
Rohan Shailesh Modi	TUMI E-Bus Mission GIZ

PHOTO CREDITS

Cover: WRI Brasil
Figure 5: Oeko-Institut e.V.

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Executive summary

Increasing population and economic growth present urbanization challenges for many transitioning economies. The transport sector is currently the world´s second-largest greenhouse gas (GHG) emitter, with road transportation at present being responsible for at least 90% of emissions from the sector (Ayetor et al. 2020). Internal combustion engine modes of transportation are the current norm, but intense efforts at decarbonization are being propelled by battery electric vehicles. However, these do not alleviate the challenges of congestion on public roads. The use of public transport using battery electric busses can simultaneously alleviate these challenges faced globally and more pronounced in transitioning economies. Whiles efforts are made to increase the share of electric vehicles in public transport, it is crucial to consider circularity and end-of-life management of such technologies during the planning and procurement stages.

Oeko-Institut e.V. has been commissioned by GIZ (German Agency for International Cooperation GmbH) for the development of a measures catalogue for inclusion of circular economy principles into E-Bus planning and procurement. This task is embedded within the Transformative Urban Mobility Initiative (TUMI) and the global project “TUMIVolt – Electric Mobility from renewable energies” on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), focussing on sustainable electric mobility. The overall aim of the project is to support city and national governments in the sustainable implementation of e-mobility solutions.

The measures catalogue is designed to be a practical guide for policy makers and procurement practitioners in transitioning economies to address the needs of policy formulation, procurement tendering, maintenance, and safe disposal of non-reusable/recyclable components of e-buses. Measures outlined and discussed are:

Measure 1: Reduced concentrations of harmful substances
Measure 2: Appropriate sizing of buses and batteries
Measure 3: Battery durability and warranties
Measure 4: Battery labelling
Measure 5: Real-life testing
Measure 6: Interoperability of charging infrastructure
Measure 7: Access to battery operation data
Measure 8: Profound battery monitoring & maintenance
Measure 9: EPR-based decommissioning agreements
Measure 10: Encouraging battery reuse
Measure 11: Sound battery end-of-life management

While the changing and advancing technological landscape of electric buses is acknowledged, a baseline of specifications, tender clauses and strategies are provided to ensure that planners and procurers are cognizant of key factors to consider during planning, procurement, operations, and disposal phases of their sustainable transport transition.

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1. Project background and introduction

Sound and well-functioning transport systems are a key public service and a major safeguard for sound urban development. While the use of private passenger cars is still common in urban agglomerations around the world, it is increasingly obvious that such private motorised transport has its limits due to high space requirements. Public transport systems are much more efficient in this regard and a major means to alleviate congestion problems. Next to space requirements and traffic congestions, air pollution from combustion engines is a major issue in most metropolitan areas. Scientific studies show that urban ambient air pollution is a major contributor to pollution related deaths, which amount to 6.5 million annually (Fuller et al. 2022). Electrification of urban transport systems is a key means of mitigating this problem and has been embraced by municipalities and transit agencies in all world regions. It is widely seen as a key means to achieve sustainable development goal (SDG) No. 11 on 'sustainable cities and communities', as well as SDG No. 3 on 'ensuring healthy lives and promote well-being for all'.

While the increasing use of electric buses has manifold advantages, it is also important that buses and their batteries are chosen and managed in the best possible manner to ensure that related investments yield maximal benefits to municipalities, transit agencies, operators, as well as to users and the wider urban societies. The subject of battery and end-of-life management is also important because there is increasing evidence that unsound management of end-of-life vehicles, e-waste and batteries can have a major detrimental effect on human health and partly already jeopardises health gains such as from improved sanitation (Fuller et al. 2022). Measures contributing to an improved management of products and materials, to minimise the use of resources and generation of waste, and to prevent detrimental effects on human health and the environment are commonly summarised under the term 'circular economy'.

This measures catalogue aims at supporting decision-makers around procurement and operation of e-buses to plan and implement circular economy aspects in this field. To do so, it introduces into aspects around the circularity of e-buses and their batteries (chapter 2) and proposes various measures that can be taken by municipalities, procurement agencies, transit agencies and e-bus operators to advance circular economy in this field (chapter 3).

The measures catalogue is held in a concise format focusing on main concepts and approaches without deep dives into technological details. The scope of the measures catalogue entails design aspects and management and recycling processes that are currently feasible and established in various lead markets and that can be implemented by transit agencies and fleet managers under existing framework conditions. Further strategies and measures are additionally possible but are not covered by this measures catalogue. These mostly require a wider change in framework conditions, which is likely to reach beyond the influence of transit agencies and fleet managers. However, given the fast-paced evolution of battery technology as well as legislation currently under review by the EU and other jurisdictions, the following areas could be beneficial to be included in future tenders for e-buses:

- Using batteries with a high recycled content;
- Using e-bus batteries as grid buffer during parking (vehicle to grid);
- Using renewable energy for e-bus charging.

The described measures can either be planned and implemented individually or, where possible, as a comprehensive package. In any case, national and local framework conditions always need to be considered additionally.

The content of this catalogue is based on case studies, published literature, as well as practical experiences from various transit agencies, e-bus operators and battery and recycling experts. The measures catalogue was developed within the TUMI (Transformative Urban Mobility Initiative) E-bus mission financed by the German Federal Ministry for Economic Cooperation and Development and implemented through the German Development Cooperation (GIZ GmbH).

2. The circular economy concept and e-buses

2.1 Circularity and the waste hierarchy

The concept of a circular economy aims at maintaining the value of products and materials for as long as possible, minimising the use of resources and generation of waste, and to keep resources within the economy after products have reached the end of their life cycle (adapted from (European Commission 2015)). This concept is widely approved and increasingly referred to by policymakers all over the world. In contrast to traditional waste management concepts that focus on the management of generated waste (recycling, energy recovery, disposal), circular economy starts with system and product designs to anticipate and support a long and efficient use of products, to support repair and reuse and facilitate recycling in the end-of-life phase.

While there are multiple ways to illustrate circular economy approaches, the 5-step waste hierarchy provides useful guidance for day-to-day decision making (see Figure 1):

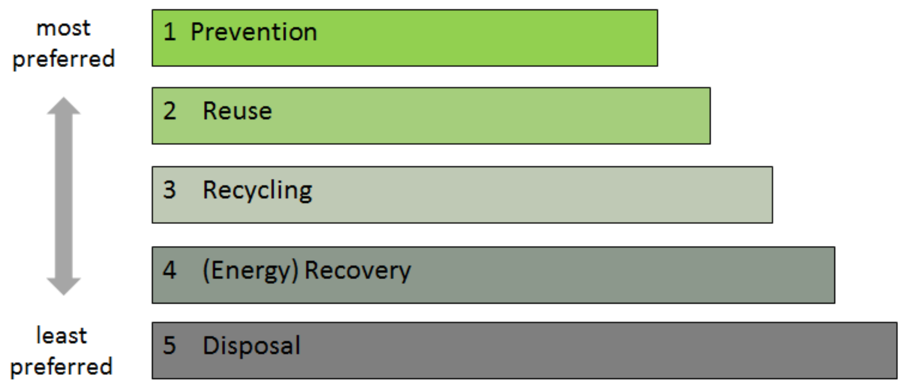

Figure 1 The 5-step waste hierarchy

Source: Oeko-Institut

It basically indicates that circular economy reaches beyond waste management and that efforts to prevent the generation of waste and to allow reuse shall be given priority over traditional waste management. We encourage to use this systematic as an underlying concept for decisions around e-bus procurement and management. Suitable measures on this are presented in chapter 3.

2.2 The concept of Extended Producer Responsibility

The concept of Extended Producer Responsibility (EPR) is closely interlinked with circular economy approaches. It implies that companies that bring products onto a national market for the first time are responsible for organising and financing environmentally sound end-of-life management. While EPR principles have been translated into binding legislation for various product groups such as electrical and electronic equipment and packaging in various jurisdictions, they are also applicable to vehicles: In the European Union for example, producers and importers of vehicles are either obliged to meet all (or a significant part) of the costs to ensure that end-of-life vehicles are delivered to authorised treatment facilities, or to run an own take-back scheme free of charge to consumers (European Union 2000). Furthermore, the EU Battery Directive specifies that EV batteries (that are classified as 'industrial batteries') are to be taken back by producers free of charge to channel them to environmentally sound waste management facilities (European Union 2006b).

In that context, it must be considered that the scrap value of end-of-life electrical buses might be strongly influenced by safe transport and recycling requirements for the batteries (Slattery et al. 2021). Particularly in places without one-stop-shop solutions for end-of-life battery management (reuse/repurposing/recycling), such transport costs can be quite high and may cause the net value of the vehicles and batteries to be clearly negative[1] . This might put a high burden on municipalities and/or transit agencies if not taken care of by other players. Therefore, it is recommended to clarify responsibilities for end-of-life management of e-buses and batteries already in the procurement phase and enter into agreements that the vehicle providers (producers or importers) accept this responsibility and take over all related tasks and costs (see section 3.9).

[1] A negative net value indicates that the total costs for environmentally sound end-of-life management are higher than the resulting value from (component) reuse and raw material recovery (also see section 2.3.3).

2.3 Basic considerations on e-bus batteries

The appearance of battery electric busses (BEBs) usually widely resembles those of conventional buses with a steel chassis, glass windows and interior fittings from metals and plastic (handles, seats…). However, the drivetrain and its auxiliary devices differ by:

- One or more electric vehicle battery packs (sometimes also referred to as 'traction batteries');
- An electric motor;
- Electric and electronic components, including other auxiliary devices such as charging port and cables.

In terms of product quality and durability, the batteries deserve particular attention as the batteries' energy content widely determines the range of e-buses. Aspects around durability, maintenance, and feasibility for reuse/repurposing of batteries have a significant influence on the total battery lifetime and subsequently circularity and long-term cost structure of e-bus deployment.
The batteries of BEBs are either integrated into the vehicle's floor, in a compartment at the back of the bus, or mounted to their rooftops (see Figure 2). Rooftop design is most common in modern BEBs. It is noteworthy that the battery packs account for nearly 40% of the manufacturing costs of e-buses (Report Linker 2021).

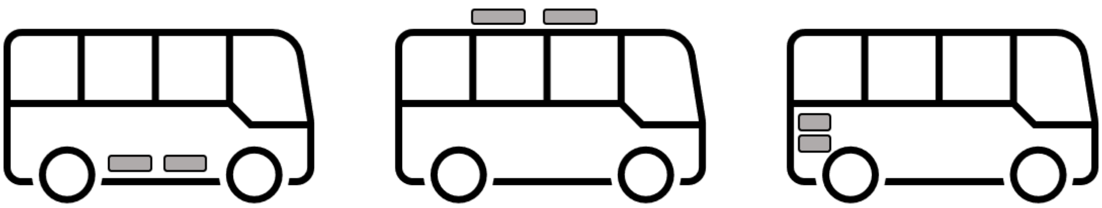

Figure 2 Ways of integrating battery packs into e-bus designs

Source: Oeko-Institut

2.3.1 Battery types and designs

Electric buses are powered by Li-ion batteries, with NMC and LFP chemistries clearly dominating the market. While NMC batteries have higher energy densities and allow a higher mileage per battery weight (see Table 1), cost factors currently clearly favour LFP batteries. These cost advantages are mainly due to the cathode materials, which account for a major part of the production cost of Li-ion battery cells (avicenne energy 2019). Lithium, cobalt and nickel are by far the most expensive battery materials, with world market prices ranging between 8,000 – 80,000 US$/t for lithium[2], 30,000 – 80,000 US$/t for cobalt and 15,000 – 35,000 US$/t for nickel (DERA 2022), which explains why cobalt- and nickel-free LFP batteries are substantially cheaper.

Battery chemistry		**Cathode materials**	**Specific energy densities (battery packs)**
NMC	Lithium-nickel-manganese-cobalt oxide	Li, Ni, Mn, Co	150 – 260 Wh/kg
LFP	Lithium-iron-phosphate	Li, Fe, P	90 – 180 Wh/kg

Table 1 Lithium-ion battery chemistries commonly used in electric buses

Source: (Battery University 2021; Wunderlich-Pfeiffer 2022; electrive.net 2022)

These cost factors, combined with high raw material prices and recent improvements in LFP energy densities led to a rapidly increasing global market share of LFP batteries from 5% in 2019 to around 40% in 2022 across all Li-ion battery applications (Wunderlich-Pfeiffer 2022).

BEBs are usually equipped with batteries with energy contents ranging between 60 to 564 kWh (Gao et al. 2017; Miaja et al. 2022), which – depending on the chosen battery chemistry – requires battery packs with a total weight ranging between 400 kg and 3200 kg per bus. Electric bus batteries consist of various modules, which are again assembled from various cells (see Figure 3). Each battery (which is commonly referred to as a vehicle's 'battery') is equipped with a battery management system (BMS). Battery packs also entail a contact system, a protective case and a thermal management system (with e.g., aluminium parts or water systems that take up and remove generated heat). Cells are often prismatic, but may also use prismatic or cylindrical designs.

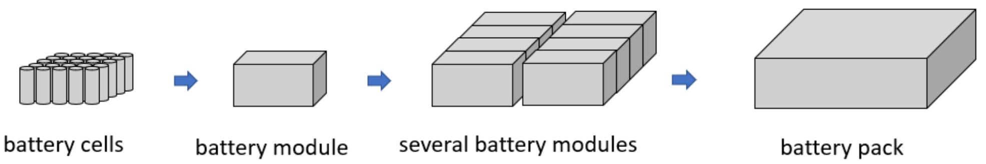

Figure 3 Composition of e-bus battery packs (simplified)

Source: Oeko-Institut

2.3.1 Battery charging models

There are two main ways of charging the batteries of BEBs, which may also be used in combination:

- Overnight charging: The buses are connected to a charging infrastructure in a bus depot during inactivity (typically late-night hours).
- On-route charging: The buses are charged during their operation at distinct charging stations such as route turning points that allow short periods of stationary charging.

[2] Lithium-carbonate, 99% Li_2CO_3

This type of ‘fast charging’ typically requires a high rate of power of up to 400-500 kW (Gao et al. 2017).

In addition, e-buses usually have regenerative braking ability so that kinetic energy is partly converted back into electric energy during breaking operations.

2.3.2 End-of-life challenges around e-bus batteries

A well planned and controlled end-of life management of Li-ion batteries – including a long use-phase and the promotion of second-life applications – is required for a variety of reasons:

- All types of Li-ion batteries contain various constituents that can have considerable negative impacts on human health and the environment if not managed properly (e.g., released to the environment). Therefore, end-of-life Li-ion batteries are classified as hazardous waste in many jurisdictions. Waste reduction measures (e.g., reuse) and environmentally sound recycling are key response strategies in this field.
- Li-ion batteries contain raw materials that are considered as critical for economic development and expansion of green energy technologies. This includes lithium, graphite, nickel, cobalt and copper3 (also see Table 1). A long use of batteries reduces the need for new battery production and subsequently raw material demand. After their final end-of-life, recycling is required to recover as many of the embedded raw materials as possible[4].
- Used and end-of-life Li-ion batteries are associated with fire safety risks. Battery cells with residual charge may overheat, catch fire and even explode after damages. This risk is also referred to as ‘thermal runaway’ of batteries and may occur days or sometimes even weeks after a damage happened. Fire risks from used and end-of-life Li-ion batteries are a major concern of waste managers and recyclers worldwide. As BEBs contain quite large battery packs (see section 2.3.1), self-ignition of individual cells can propagate and cause quite large battery fires.
- During the use of batteries in e-busses, the capacity of the battery will decrease over time until it is no longer suitable for the operation of the vehicle. However, such batteries may still have enough “life”, to allow their use in other applications, such as stationary energy storage systems for lower power applications, e.g., storing renewable energy generated from solar, wind, etc. Such second-life use can help maximise the duration that the battery resources are used and thus contributes to resource efficiency and circularity.

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[3] Nickel and cobalt are not used in all types of Li-ion batteries.

[4] A perfect recovery of all embedded raw materials is not possible mainly due to complex material compositions and entropy challenges. Recyclers usually focus on the recovery of copper, cobalt and nickel as the main value-carriers of lithium-ion batteries, but, depending on applied processes, may also be able to recover some of the embedded aluminium and lithium. Other materials such as manganese and graphite are typically lost in Li-ion battery recycling (Brückner et al. 2020).

2.3.3 Economics of end-of-life battery management

Sound end-of-life management can be motivated by a combination of four main factors:

1) The reuse value of batteries or some of their components
2) The value of raw materials recovered during recycling
3) Legal obligations to conduct sound end-of-life management
4) Other obligations to conduct sound end-of-life management (e.g., by contract partners)

In that context, the following aspects must be considered:

- The future **reuse value** of used electric vehicle batteries is subject to multiple uncertainties. To date, reuse and repurposing operations often struggle with multiple different battery designs[5], insufficient access to battery state of health data and issues around second-life product safety (Zhu et al. 2021). While reuse and repurposing operations might allow a certain profit margin in the future, this has not yet been proven on a larger scale
- The **material value** of end-of-life vehicle batteries is often limited to some few recoverable metals, most prominently copper, cobalt and nickel. The trend to LFP cell chemistries (see section 2.3.1) also means that such batteries have a significantly reduced material value that currently does not allow to cover the costs for recycling processes. Therefore, recyclers charge gate fees for LFP batteries, indicatively ranging around 2000 €/t (Manhart et al. 2022). Lithium is only contained in comparably small concentrations and is not recovered in most existing recycling processes (Brückner et al. 2020; Sojka et al. 2020).
- **Safe transport and storage** of EV-batteries to repurposing and recycling is associated with considerable efforts and costs. As described in section 2.3.2, fire and explosion risks are considerable. Stimulated by various incidents, national and international bodies as well as transport and insurance companies are about to develop guidelines and regulations for transport of used and end-of-life EV-batteries. While reverse logistics will surely adapt to growing volumes and tightening safety requirements, related costs are likely to be substantial, particularly when batteries require large transport distances (Slattery et al. 2021) and/or movement across international boundaries. In the latter case, also a notification according to the prior-informed-consent-procedure of the Basel Convention is required, that can be associated with considerable administrative efforts and delays (Prevent & StEP 2022).

It should therefore be considered that environmentally sound end-of-life management will likely be associated with net costs. Implementing the measures of this catalogue can help to reduce efforts and costs for municipalities and transit agencies and to ensure that related burden is taken over by those players supplying e-buses and batteries in line with the concept of Extended Producer Responsibility (see section 2.2)

[5] Sometimes even design not allowing to remove battery modules or cells.

2.4 Generic end-of-life management of e-bus batteries

Figure 4 gives a generic overview of an ideal management pathway of e-bus batteries:

- After procurement of e-buses, regular maintenance of buses and batteries is conducted to enable a long first use phase. Compared to the maintenance of conventional buses, e-buses require less efforts in terms of physical inspections and maintenance, but more in terms of battery monitoring and balancing, which can be done through remote data access.
- After the batteries have reached a remaining capacity and power output that are too low for bus operation, the battery packs are removed, safely packed, and shipped to an authorised battery testing and treatment facility.
- Ideally, the receiving company has sufficient information from the Battery Management System on the battery's history and state of health and can take informed decisions on the further use of batteries and modules. Reusable battery packs and modules are used for second-life storage solutions (also referred to as 'repurposing'). Other modules and battery components are passed on to recycling.
- After several more years of second-life use, batteries have no relevant reuse value anymore and are also sent to recycling.
- Recycling commonly starts with a manual dismantling of larger battery packs. Further processing is done under safe conditions in a sealed environment, including dust and emission controls. Most recycling processes entail mechanical pre-processing where the battery modules and cells are shredded and sorted into major output fractions, namely steel, cooper, aluminium, plastics and black mass.
- Aluminium, copper and black mass are passed on to smelting and/or refining processes that generate raw materials for industrial production.

In addition to the points above, used and end-of-life batteries must also be discharged prior to processing. This discharging can either be conducted prior to shipment (at the point where the batteries are taken out of the bus fleet), or as a first management step before dismantling. In any case, discharging and dismantling of electric bus batteries are high voltage operations and shall only be carried out by trained personnel.

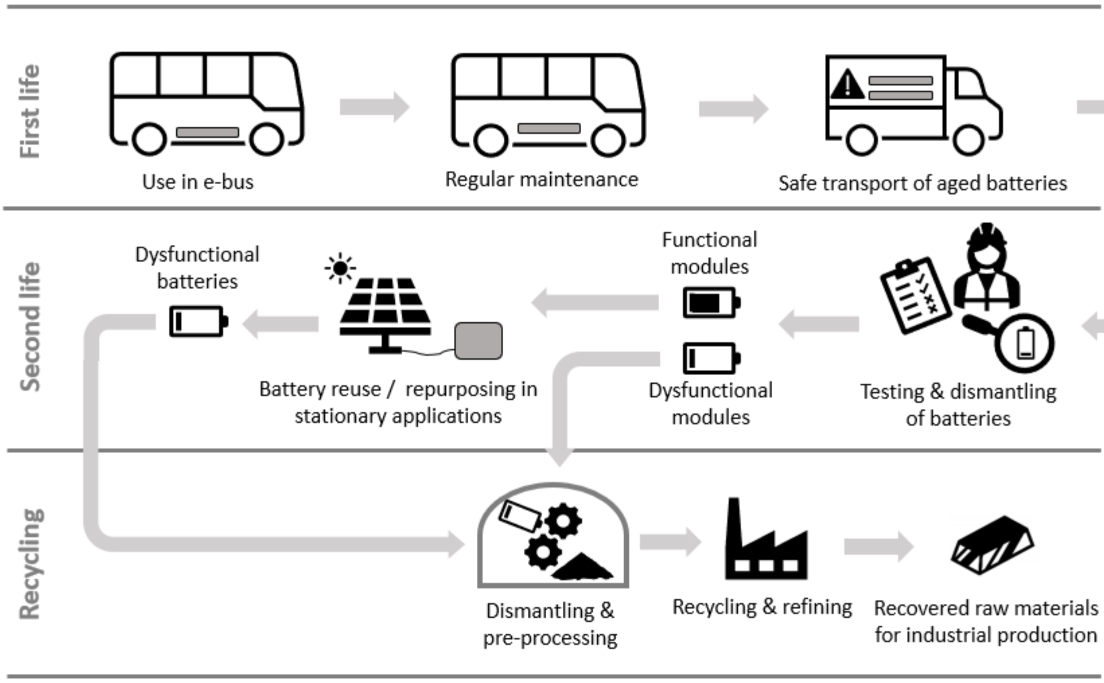

Figure 4 Ideal management pathway of e-bus batteries

Source: Oeko-Institut

2.5 End-of-life challenges of selected other e-bus components

2.5.1 Tyres

Used and end-of-life car and bus tyres are a widely unresolved waste stream in many countries and world regions. While some used car tyres may find a second use (e.g., boating fenders, furniture production), recycling options are limited to some few downcycling[6] options such as the production of mats. In a worst-case scenario, used tyres are burned openly, which is either done to reduce waste volumes or to recover the embedded steel mesh to be sold to steel recycling plants. Such practices are highly polluting and should clearly be discouraged/banned.

Tyres have a very high calorific value and may serve as refuse derived fuel (RDF) in industrial processes. Quite commonly, waste tyres are used to fuel cement kilns. This management pathway (energy recovery) is at the second lowest level of the waste hierarchy (see section 2.1), and commonly helps to replace coal as the main fuel type in cement production. If this management pathway is chosen, it must be ensured that emission profiles of cement kilns are in line with national and international good practices and can cope with such changes in fuel composition.

2.5.2 Cables

Cables have metal cores (mostly from copper or aluminium) and are insulated with plastics. The type of plastic for the insulation varies greatly, but often consists of PVC or

[6] The term 'downcycling' describes recycling operations that lead to a material of lower quality.

PE with various additives being applied too. Most scrap markets ask suppliers to deliver the metal core liberated, without any remaining insulation. While this plastic insulation can be removed by mechanical means (e.g., peeling, stripping, granulation, and sorting), related operations are either labour-intensive or require investments in machinery. Thus, informal sector operators sometimes resort to open burning of cables. Such open burning generates considerable pollution, including the formation and emission of highly hazardous persistent organic pollutants (POPs). Such POPs generation is particularly relevant for cables insulated with chlorine-containing PVC.

Figure 5 Open burning – a very polluting way to treat waste cables

Source: Oeko-Institut

2.5.3 Electronic components

Electrical and electronic components contain a wide range of materials and substances, many of which have hazardous properties. Electronic components such as printed wiring boards with microchips have relevant concentrations of copper and precious metals and are therefore sought after by scrap dealers and recyclers. In general, it is important that electrical and electronic components are not disposed or recycled in uncontrolled operations, which is quite polluting and also inefficient in terms of raw material recovery.

2.5.4 Plastics

Plastic parts and components are used in many parts of buses, in particularly for the interior (e.g., interior lining, seats, cushion). While many plastic types can theoretically be well recycled, there are multiple practical problems for doing so in real-life applications:

- Many used plastics are coated or blended, making sound separation of polymers difficult or even impossible.
- Additives such as flame retardants may limit the use of recycled plastics and create obstacles for using recycled plastics.
- End-of-life vehicles are dismantled or shredded with a primary focus on recovering metals. Less valuable materials end up in the so-called 'shredder-light fraction', which consists of a large variety of materials commonly only used for energy recovery (if at all).

Nevertheless, some materials may have a considerable recycling potential. Amongst others, interior plastic parts of vehicles are often made from ABS-PC, which is a quite valuable engineering polymer. Furthermore, parts such as bumpers are commonly made from PP. In case these materials can be retrieved in a pure form and are not contaminated with flame retardants or other critical additives, they might hold a considerable recycling potential. Similar potentials might also exist for polyamide (PA) elements such as carpets and seat covers.

2.5.5 Refrigerants

All air conditioners use refrigerants. While old and ozone depleting refrigerants have been globally banned, commonly used substitutes still have a very strong global warming potential when released uncontrolled. R134a, for example, has a global warming potential 1430 times higher than CO_2. Refrigerant leakages from air conditioning systems are very common and may occur during normal operation, accidents or decommissioning so that – in most life-cycle scenarios – a full emission of refrigerants must be assumed[7]. Common public buses contain around 10 kg of R134a (BMU & UBA 2011), which means that a full emission has an impact on global warming equivalent of around 10 t of CO_2 per bus. Substitutes with significantly less global warming potential are readily available and include R1234yf and CO_2. In the European Union, the use of refrigerants in vehicle air conditioning is limited to substances with a global warming potential not higher than 150 times that of CO_2 (European Union 2006a). It is therefore recommended to aim for e-busses that exclusively use such climate-friendly substitutes (see section 3.1).

[7] Assuming a full emission may even be a conservative estimate as refrigerants are commonly refilled during inspection and maintenance. Hence, a bus's life-cycle emissions might be significant.

2.5.6 Other pollutants

Vehicles may contain a number of other substances of concern, which may be released to the environment during or after end-of-life treatment. As a reaction, the European Union has banned the use of some hazardous substances, particularly the heavy metals lead, mercury, cadmium and hexavalent chromium from being used in vehicles. The ban allows certain exemptions such as the use of certain heavy metals concentrations in alloys and lead in lead-acid batteries. The exemptions are periodically reviewed (European Union 2000).

3 Measures for improved circularity of e-bus batteries

3.1. Measure 1: Reduced concentrations of harmful substances

What?	Design and use of buses that have reduced contents of hazardous substances
Why?	Hazardous substances can have detrimental effects on human health and the environment, particularly during the end-of-life phase. Furthermore, such substances are often obstacles for high-quality recycling.
Policy relevance	High: Substance regulations and bans are most effective when imposed and enforced through national legal framework

Procurement of electric buses offers the opportunity to select models that entail reduced concentrations of harmful substances and facilitate end-of-life management in this field. Due to binding legislation in the European Union[8] and some other jurisdictions, the global vehicle market has already developed solutions to manufacture vehicles widely free from the heavy metals cadmium, lead, mercury, and hexavalent chromium, and with air conditioning without strong greenhouse gases (see sections 2.5.5 and 2.5.6).

Box 1 proposes a text for e-bus procurement that is widely based on the established passenger vehicle regulations in the European Union, so that many e-bus manufacturers should already be familiar with related requirements. It is noteworthy that the requirements of Box 1 are not only applicable to e-buses, but may also be used for other vehicles, including passenger vehicles and vehicles with conventional combustion engine.

[8] The requirements on refrigerants are based on the EU Directive 2006/40/EC related to emissions from air-conditioning systems in motor vehicles (MAC Directive). The other substance-related requirements are based on EU Directive 2000/53/EC on end-of-life vehicles (ELV Directive).

Box 1: Draft criteria for procuring e-buses with reduced concentrations of harmful substances

The air conditioning of buses shall use a refrigerant with a global warming potential not higher than 150 CO_2 equivalents.
In addition, electric buses shall not contain lead, mercury, cadmium, or hexavalent chromium. Exemptions are possible for:

- Lead as an alloying element in the following applications:
  - Steel for machinery purposes and batch hot dip galvanised steel components containing up to 0.35% lead by weight
  - Aluminium alloys with a lead content up to 0.4% lead by weight
  - Copper alloys containing up to 4% lead by weight
- Lead and lead compounds in the following components:
  - Lead in lead-acid batteries
  - Lead in high melting temperature type solders (i.e. lead-based alloys containing 85% by weight or more lead)
  - Electrical and electronic components which contain lead in a glass or ceramic, in a glass or ceramic matrix compound, in a glass-ceramic material, or in a glass-ceramic matrix compound
  - Lead in PZT-based dielectric ceramic materials of capacitors being part of integrated circuits or discrete semiconductors
- Hexavalent chromium in the following applications:
  - Hexavalent chromium as an anti-corrosion agent of the carbon steel cooling system in absorption refrigerators up to 0,75% by weight in the cooling solution:
    - designed to operate fully or partly with electrical heater, having an average utilised electrical power input ≥ 75 W at constant running conditions;
    - designed to fully operate with non-electrical heater.

In case further exemptions for the use of lead, mercury, cadmium or hexavalent chromium are needed, they should be specified in the offer, including a technical justification for each requested exemption. An exemption may only be granted in case it is convincingly explained that substitution would either have negative impacts on product safety or would create more environmental harm.

3.2 Measure 2: Appropriate sizing of buses and batteries

What?	Procure e-bus models that are adapted to the local realities
Why?	Ensure that e-bus model(s) are suitable for local requirements so that long-term usability is given
Policy relevance	Low: Appropriate sizing of e-buses and batteries depends on the local conditions and demands and cannot be determined on a central policy level.

The battery energy content determines the range of a BEB: The larger the capacity, the longer the distance a bus can cover without additional charging. A long use phase of e-buses significantly helps to avoid the production of new transport vehicles and is in line with the waste prevention concept that is given highest priority in the waste hierarchy (see section 2.1). Due to the high-cost implications of batteries (see section 2.3.1), battery oversizing is to be avoided. Nevertheless, under sizing is also a risk, as undersized battery capacity may significantly impact the bus's functionality: Buses that cannot complete a full day of operation may require the purchase of back-up bus capacities, or even a full replacement.

In terms of battery capacity and bus mileage, the following aspects should be considered in the procurement stage:

- Hot and cold weather conditions have impacts on BEB performance and mileage. Amongst others, this is due to required electrical heating or cooling of the passenger cabin (Wang et al. 2020). In cold conditions (-5°C to 0°C), reduction may be as much as 38% (Henning et al. 2019) with similar effects in hot climates. In addition, battery charging consumes more time in hot conditions, which may effectively limit on-rout recharging effectiveness (McGuffie 2021).
- Energy requirements and range also depend on the terrain a bus is used in. In a flat environment, BEBs usually achieve a higher range than in hilly terrain (Wang et al. 2020).
- Battery capacities degrade over time. Vehicles (or their batteries) are commonly replaced when the capacity has dropped to significantly below 80% of its original value. This means that the bus range also reduces over time to around 70% to 80%.
- Based on available studies, it can be shown that unstable and unpredictable vehicle manoeuvres such as experienced in traffic congestions result in a decrease in the expected battery State of Health. (Wang et al. 2020). Dedicated bus lanes can therefore not only increase the service quality of public transport systems, but also support long battery lifetimes.

All the above factors can cause buses to operate under their expected range and mileage. Such negative scenarios can be mitigated by one or more of the following measures:

- Specify real-life operating requirements (temperature ranges, terrain, additional weight like passengers, etc.) in tender documents and require bidders to guarantee a defined BEB mileage for the given conditions and a pre-defined time period (also see Box 2).
- Use new BEBs for longer and more (energy) demanding routes. Once the battery capacity has degraded, they can be shifted to shorter and less energy-demanding routes.

Box 2: Good practice example – quality requirements for e-buses in the city of Leipzig

The City of Leipzig (Germany) works on a gradual transition of its bus fleet to battery electric buses. Buses are procured, owned and operated by the Leipziger Verkehrsbetriebe, which is a municipality-owned transport agency. In its tendering strategy, the Leipziger Verkehrbetriebe require that suppliers must guarantee that the buses and their batteries achieve minimum performance requirements for ten years of constant operation. Instead of solely using indirect performance indicators (e.g., at least 80% of remaining battery capacity after a defined number of years), tender and contract specifications require that e-buses can – after ten years of constant operation under the given conditions in Leipzig – still cover a distance of 80 km with one battery charge. The 80 km are derived from typical operating conditions in Leipzig, which uses a combination of depot- and on-route charging. Further operating conditions in Leipzig are also specified in the tender documents, including information on terrain and prevailing temperature ranges. In case one or more supplied e-buses fail to meet this requirement, the supplier is contractually required to provide remedy such as a replacement of the battery.

3.3 Measure 3: Battery durability & warranties

What?	Ensure that only high-quality batteries are used in e-buses
Why?	High-quality batteries have longer lifetimes, need less frequent replacements and are therefore more resource and cost efficient
Policy relevance	High: Minimum durability requirements can be integrated in national legislation on batteries and/or vehicles

While measure 2 sets incentives to supply high-quality buses, it cannot be ruled out that bidders present lower-quality solutions in terms of batteries, while accepting more frequent equipment replacements often at the procurer's cost. Although such a strategy might follow some narrow economic considerations, it is obviously in conflict with circular economy principles and has negative side-effects on the wider economy and society (see chapter 2). To effectively prevent the use of sub-standard batteries, minimum durability requirements can be introduced in tendering documents. Minimum durability criteria for electric vehicle batteries (including those of e-busses) were developed by the United Nations Economic Commission for Europe (UNECE) in 2022 and are summarized in Table 2.

Vehicle age/km	State of certified energy[9]
From start of life to 5 years or 100,000 km, whichever comes first	80 %
Vehicles more than 5 years or 100,000 km, and up to whichever comes first of 8 years or 160,000 km	70 %

Table 2 UNECE minimum performance requirements for electric vehicle batteries

Source: (UNECE 2022)

Nevertheless, the current ambition level of the UNECE requirements is not suitable as minimum requirement for e-bus batteries[10]. Data from producers and users of electric buses indicate that lifetimes of > 10 years are possible with existing batteries and e-buses (MassTransit 2015; Aamodt et al. 2021). Advances in technology and competition among manufacturers will continue to increase the lifetime and quality of batteries even further. It is therefore recommended to request more ambitious performance and durability requirements in tender documents and contracts; indicatively for around 12-15 years of e-bus operation. This should be based on current industry information on warranties and performance specifications of batteries from major suppliers. If no criteria based on market information can be derived, the minimum criteria from the box below might be used as a starting point[11].

Box 3: Draft criteria for procuring e-buses with durable batteries

The supplier shall ensure that the e-bus batteries' State of Certified Energy (SOCE) is in-line with the following minimum performance requirements or better:

Vehicle age/km	State of Certified Energy
From start of life to 6 years or 400,000 km, whichever comes first	80 %
Vehicles more than 6 years or 400,000 km, and up to whichever comes first of 10 years or 500,000 km	70 %

The supplier shall submit evidence of compliance through independent test protocols in line with verification methods and procedures set out in the United Nations Global Technical Regulation on In-vehicle Battery Durability for Electrified Vehicles.

[9] "State of certified energy" (SOCE) means the measured or on-board usable battery energy performance at a specific point in its lifetime, expressed as a percentage of the certified usable battery energy (UNECE 2022).

[10] There might be revised UNECE criteria suitable for e-bus batteries available in the future. Therefore, consulting UNECE information could be helpful while developing battery durability and warranty criteria.

[11] A brief market survey performed in 2023 indicates that EV manufacturers have already gone to market with 6- to 12-year warranties with unlimited mileage; hence the minimum figures presented are easily achievable by industry (MassTransit 2015).

3.4 Measure 4: Battery labelling

What?	Ensure that e-bus batteries carry labels and QR-codes providing information on battery characteristics to third parties engaged ion reuse/repurposing and end-of-life management.
Why?	Easy access to information on battery characteristics can support sound decision-making in end-of-life management.
Policy relevance	High: Battery labelling is most effective when applied uniformly across all e-vehicle types. This is best achieved through industry standards combined with mandatory roles to apply such standards

Companies taking overused and end-of-life vehicle batteries require information on their characteristics to take meaningful decisions on handling and management pathways, thereby helping to optimise end-of-life management.

Battery-specific information can be provided by the producer in a way any third party can get easy access to it. This aspect has already been taken up by many fora and initiatives and is discussed under the keyword 'battery passport'. While there is not yet any established format for such a battery passport, California will start requiring electric vehicles registered from 2026 onwards that batteries are labelled with a digital identifier (QR code) that links to online information on the battery chemistry (cathode and anode type), manufacturer, date of manufacture, minimum voltage, and rated capacity (California Code of Regulations 2022). A similar approach is taken by the Draft European Battery Regulation and may foresee a mandatory battery labelling with such QR codes by 2027 (European Commission 2020). Also, China already has (and is planning to expand) EV battery labelling requirements (Bej et al. 2022).

While such labelling can be a useful tool to support end-of-life management, systems are not yet established in a uniform manner. Nevertheless, it can be required that producers of e-buses provide information on the batteries in an easily accessible manner (see Box 4).

Box 4: Draft criteria for the labelling of e-bus batteries

The producer shall equip all battery packs with a well visible and accessible label / digital identifier (e.g., QR code) linked to a data website given information on at least the following battery characteristics:

- the battery chemistry (cathode and anode type)
- the manufacturer
- the date of manufacture
- the minimum, maximum and mean voltage
- the rated capacity

The website shall retain the information for at least 15 years from the date of manufacture and shall be made publicly accessible without any charge and registration procedure.

The labelling and information provided shall further be aligned with common industry formats for this purpose, including the size, design and placement of the labels, and the format of digital data provision. Information on further battery characteristics shall be additionally provided through the system in line with established practices and legal requirements.

3.5 Measure 5: Real-life testing

What?	Testing of e-bus prototypes prior to final procurement decisions
Why?	Ensure that e-bus model(s) are suitable for local requirements so that long-term usability is given.
Policy relevance	Low: Real-life testing is meant to test vehicle suitability for a specific local context. Central policy approaches have limited effects here.

Measure 2 already stresses the need that buses must suit local needs and be capable to robustly operate in the given environment. While many such related aspects can and should be specified in tender documents (e.g., route lengths and characteristics, charging modes, ambient temperature ranges), there are numerous aspects and bus characteristics that can be overlooked in the process, but that might turn out to be relevant in day-to-day operation, such as passenger numbers and additional baggage. In that context, transit agencies and operators can aim at testing new e-bus models prior to purchase orders. In most situations, producers will – for understandable reasons – only be willing to grant test drives under controlled conditions (without passengers, not in routine operation), a practice which can already reveal a lot of practical aspects of bus suitability and greatly support the selection of suitable models as described in section 3.2. In case larger numbers of buses are to be procured, producers may also agree to real-life tests in day-to-day operation.

Box 5: Good practice example – testing of bus prototypes in India

In India, five large cities (Delhi, Calcutta, Surat, Bengaluru, and Hyderabad) joined forces in their efforts to procure electric buses. In this 'Grand Challenge', a total number of 5450 electric buses were procured through one tender process. While this large volume enabled a significant discount of unit prices, it also allowed to introduce further tendering requirements. Amongst others, the tendering process considered an interim stage in which the three best-rated supplier candidates were asked to provide prototypes for real-life testing. The results of this testing were used in the final selection of the supplier (Modi 2022).

A comparable large-scale follow-up tender for electric bus operation has been published in 2022 (6465 e-buses) and another one is planned for 2023 (~5000 e-buses) (Convergence 2022). Such demand bundling opens significant possibilities to request circular economy requirements including those described in all other recommended measures.

3.6 Measure 6: Interoperability of charging infrastructure

What?	Ensure interoperability of charging infrastructure with different e-bus models
Why?	Interoperable charging systems can be used for a wide variety of e-bus models and therefore have usually a long lifetime, which supports resource conservation and long-term cost reduction.
Policy relevance	High: Policymakers can regulate the interoperability of charging interfaces and protocols on a central (national) level.

In many cases, procurement of e-buses and provision of charging infrastructure is tendered as a package – at least in the initial phase of e-bus deployment in a certain location. While this procurement strategy has many advantages, it is important to consider that charging systems should be designed in a way that can also be utilised for e-bus models from other manufacturers that may complete the fleet at a later point in time. Without interoperable charging infrastructure, an e-bus fleet might either depend on a very limited number of e-bus suppliers or might be forced to install a parallel charging infrastructure for other e-bus models. It is therefore of high importance to install interoperable charging infrastructure.

To do so, a transit agency / fleet manager must first decide on the type of charging intended to be applied in a certain city and mainly choose from the following options

- Plug charging (conductive) / pantograph charging / inductivity charging
- Depot charging / depot charging + on-route charging

When physical infrastructure is already in place, the following aspects should be considered:

- Charging types and methods (Conductive: AC/DC or Inductive)
- Output power

- Charging interfaces of both the charging station and E-bus (outlets, inlets, connector faces)
- Communication protocol between the charger and battery of the electric buses

The outlet of the existing charging stations should match the outlet of the new fleet. On the contrary, the infrastructure should be adapted to ensure continued operation in both new and old buses. Considering these aspects, interoperability criteria must be specified in tender documents. When charging infrastructure is in place, the tender must include obligations to provide the necessary converters and adapters or modifications for ensuring the interoperability and compatibility with the fleet. These criteria should refer to international norms and standards related to the user interfaces, as well as the charging communication protocol. The following table gives an overview of common norms and standards in this field.

Standard	Description
Connectors, Inlets, Plugs	
IEC 62196	International standard series for plugs and sockets for electric vehicle charging
SAE J1772	North American standard for electrical connectors for electric vehicles maintained by SAE International: SAE Electric Vehicle Conductive Charge Coupler.
GB/T 20234	Chinese national standard for Connection Set for Conductive Charging of Electric Vehicles.
CHAdeMO	Japanese DC charging standard for electric vehicles.
Onboard Charger, Electric Vehicle Supply Equipment (EVSE)	
IEC 61851	International standard for electric vehicle conductive charging systems
GB/T 27930	Chinese standard for electric vehicle battery cable charging
Communication EV To EVSE	
ISO 15118	International standard on Road vehicles - Vehicle to grid communication interface (bi-directional charging/discharging)
DIN SPEC 70121	German technical specification on Digital communication between a DC. EV charging station and an electric vehicle for control of DC. charging in the Combined Charging System
DIN SPEC 70122	German technical specification on Conformance Tests for Digital Communication Between a DC EV Charging Station and an EV for Control
GB/T 27930	Chinese standard on Communication Protocols Between Off-Board Conductive Charger and Battery Management System
Wireless Power Transfer (WPT) Systems	
IEC 61980	International standard on Electric Vehicle Wireless Power Transfer (WPT) Systems
GB/T 38775	Chinese national standards for inductive or wireless charging
Communication EVSE To Charging Station Management System (CSMS)	
IEC 63110	International standard defining a protocol for the management of electric vehicles charging and discharging infrastructures (currently under development)
OCPP	Open Charge Point Protocol (OCPP)

Table 3 Overview of common standards for e-vehicle charging

Source: Adapted from Vector Informatik GmbH

Box 6: Good practice example – Interoperability of charging infrastructure in Israel

Starting in 2030, Israel has stipulated that all new buses for public transport must be fully electric. Diesel-powered buses currently account for less than 1% of total vehicles in the country, hence this goal is highly achievable. The Israeli Ministry of Environmental Protection together with the Ministry of Transport and Road Safety have coordinated their efforts to achieve this goal through a mix of regulations and standards. One important pilar of their strategy was to achieve interoperability of charging infrastructure for public and private vehicles. The government has developed mandatory standards based on EU DC charging requirements CCS-type 2 and Open Charge Point Protocol (OCPP) for communication between charging points and electric vehicles. The use of already existing and accepted standards and regulations helps with enforcement for import and registration of vehicles. To support the adoption of e-buses further, the Ministry of Transport operates depot charging stations for municipal fleets and private e-bus fleets at a fee. Business models based on depot charging are also present for both public e-bus fleets and private citizens irrespective of the brand of vehicle. Whiles this approach is successful to achieve interoperability, a shortcoming of the national policy is the 100% shift to e-busses without ensuring sufficient availability of charging stations. This situation has led to new e-buses being unused and currently warehoused which amounts to losses in profitability to the state and private fleet operators.

3.7 Measure 7: Access to battery operational data

What?	Ensure that e-bus manufacturers grant access to battery operational data
Why?	Battery operational data is key to enable a thorough monitoring of battery state-of-health and for various measures around maintenance and extension of battery lifetimes.
Policy relevance	High: Policymakers can introduce mandatory rules for battery manufacturers and electric vehicle providers to grant access to battery operational data.

Data and knowledge on the actual performance level and history of e-bus batteries is a major precondition for a sound management of e-buses and their batteries, including questions related to:

- Is a bus fit enough to serve a certain route?
- When and how should a battery be serviced/conditioned?
- What is the expected remaining lifetime of a battery?
- What can be done to expand the battery lifetime and ensure safe operation?
- If or when a battery swap is economical and sustainable?
- Is the battery performing according to the agreed warranties?
- What is the remaining value of a battery and is it suitable for a second-life application?

While bus operators and drivers usually can monitor the state-of-charge (SOC) (e.g., on a display in the bus cockpit, or through a digital remote access), state of health (SOH) information is not always accessible to the operators and users. Moreover, provided SOH data may be aggregated, limiting the user's ability to gain profound insights to fully answer the questions above.

It is therefore important that e-bus producers grant access to battery diagnostic data to their customers, including the right to pass on this data access to independent third parties (e.g., service providers for battery diagnostics, maintenance and reuse/repurposing). This data access should be requested in the tender specifications in unequivocal manner, by specifying the type of signals to be given access to, their physical unit and their accuracy and frequency. In addition, the data formats and interfaces must be specified to ensure that the data can be accessed with publicly available hardware (telematic units) and analysed with publicly available software.

It is also recommended that any shortcomings in the fulfilment of related requirements are subject to remedy and/or financial compensations.

Box 7: Draft procurement text on access to battery diagnostic data

The suppliers shall enable continued monitoring of battery diagnostic data as specified in the table below and give the client full access to this data. This also includes the client's right to extend this data access to any third party nominated by the customer.

Signal	Unit	Value resolution	Time resolution
Battery current over time	A	0.1 A	≤ 1 sec
Battery voltage over time	V	0.1 V	≤ 1 sec
Cell temperature (avg/min/max) over time	°C	0.1°C	≤ 10 sec
Cell voltage (avg/min/max) over time	V	0.001 V	≤ 1 sec
Battery state of charge (SoC) over time	%	0.1 %	≤ 10 sec
Accumulated charge throughput	As	0.1 As	≤ 60 sec

The signals indicated in the table shall be continuously sampled during operation and charging and provided in a digital format compatible with publicly available software. All signals must be time-synchronous. All signals shall be made available through a standard output interface such as CAN or FMS.

The following additional battery information must be made available to the client upon purchase:

- Name of battery pack supplier
- Nominal battery pack energy (in kWh)
- Battery cell chemistry
- Battery model or serial number
- Battery topology and wiring:
  - Nominal cell capacity (in Ah)
  - Nominal cell voltage (in V)
  - Number of modules per battery pack
  - Number of cells per module

3.8 Measure 8: Profound battery monitoring & maintenance[12]

What?	Ensure that battery operational data are used for a high-quality monitoring and maintenance of e-bus batteries
Why?	High-quality monitoring and maintenance can significantly extend the battery lifetimes
Policy relevance	Low: Battery monitoring and maintenance measures fall into the sphere of e-bus fleet operators and cannot be regulated on a central level.

E-bus and battery durability requirements can be specified through design and considered in tender specifications as suggested in Measure 3. Beyond this, also sound monitoring and maintenance of the batteries have a great influence on the total lifetime of batteries and can usually extend the first life significantly beyond the granted warranty periods.

This potential can be tapped through monitoring of operation data (see Measure 7) and by using this information for sophisticated battery diagnostics. Based on this data-driven efforts, various measures can be taken to extend the batteries' life, including planning and conduct of cell balancing and exchange of certain models or cells.

When planning battery monitoring and maintenance, it is important to opt for an organisational structure that sets incentives for a high-quality service and that encourages the service provider to enable long battery lifetimes (without jeopardising safety and quality). This may be achieved through one of the following options:

- E-bus as a service: Operators do not own the e-buses and batteries but have a contractual arrangement with a provider who also takes care of the batteries. In such settings, it is usually also in the interest of the provider that e-buses and batteries are thoroughly monitored and maintained.
- Special monitoring and servicing agreements: Operators may choose to contract a third party specialised in battery diagnostics and maintenance. The contractual arrangements should be tailored in a way that the service provider has tangible own benefits from a good service, including prolonging battery lifetimes[13]. It is noteworthy that most of the monitoring and servicing can be done remotely through access to battery operational data. Therefore, access to such data is an important prerequisite (see measure 7).

[12] Enel X 2023.

[13] While such services are also offered by many e-bus suppliers, their core interest often lays in the sale of buses and may be less pronounced in achieving lifetimes significantly above the contractually agreed warranty periods

tumi E-Bus Mission

Box 8: Good practice example – E-bus as-a-service demonstrated in Italy

In the Italian cities of Rome, Turin and Iglesias, a project is currently underway to promote the electrification of public transport through an e-bus as-a-service model (Enel X 2023). Through a private partnership, city authorities have outsourced the implementation of an e-bus service. This includes feasibility and cost/benefit analyses, financing options for the supply of vehicles, installation of charging infrastructure, operationalization of routes, and maintenance of both vehicles and batteries. Digitalization of ticketing systems and the use of data analysis to focus on decongestion of the most populated routes ensures that citizens have an enhanced experience of public transportation. While this is obviously profitable to the private partner, city authorities can ensure through privatization that electromobility experts are involved in the transition of the transport sector. With a built-in local capacity development plan, expertise can be developed over time to ensure continuity of operations when the contract with the private service provider expires, and e-buses are handed back to the local public transport office (Sustainable Bus 2022).

3.9 Measure 9: EPR-based decommissioning agreements

What?	Ensuring that costs and efforts for sound end-of-life management do not fall onto municipalities, transit agencies or bus operators. Extended Producer Responsibility shall ensure that efforts and costs for sound end-of-life management are to be covered by producers.
Why?	Sound end-of-life management of batteries may be associated with additional costs. In addition, the realisation of sound end-of-life solutions for batteries requires specific know-how that is not within the core competencies of e-bus operators.
Policy relevance	High: Extended Producer Responsibility is best introduced through nationwide mandatory systems that require producers and importers to take suitable action to take back and soundly manage wastes arising from their products.

As indicated in section 2.2, Extended Producer Responsibility is a key means to ensure that responsibilities and costs related to the sound end-of-life management of batteries do not rest with the users of such batteries. This is particularly relevant, as sound end-of-life management of e-bus batteries may be associated with net costs, which – for many operators of bus fleets – will be a paradigm shift away from a situation where old buses could always be sold for a positive price (also see section 2.3.3).

In countries where EPR systems for electric vehicle batteries are already maturely developed, transit agencies and operators may refer to existing legal obligations of producers and require that adequate provisions are taken so that batteries are collected and managed by means provided and financed by the producer or importer (of the e-buses)[14].

Although the same approach can be taken in countries without existing EPR schemes through specifying end-of-life responsibilities in tender and contract documents, there is a main challenge linked to the fact that there are several years between e-bus procurement and decommissioning: While procurement requires clearly verifiable criteria, it is hard to verify if a take-back and recycling agreement will still have chances for realisation in 5 or 10 years' time[15].

Therefore, the most reliable way to secure that end-of-life management is taken over by the producer is a procurement strategy that combines a) procurement of buses, b) maintenance and c) sound management of end-of-life equipment. Particularly the maintenance element ensures that contract partners are at display when it comes to battery decommissioning. In any case, it is important that the responsibility for sound end-of-life management is clearly specified in contractual arrangements – ideally with requirements such as those proposed in section 3.11.

[14] Additionally, the tendering and contract documents may further specify key performance indicators for end-of-life management as suggested in Box 9.

[15] Well-organized EPR schemes have in-built mechanisms in this regard. In such systems, the producers' obligations are managed through one or more registered Producer Responsibility Organizations (PRO) that keep reserve funds for future collection and recycling liabilities.

Box 9: Draft procurement text on EPR-based battery decommissioning

The supplier shall take over full responsibility for the end-of-life management of the batteries after their first use in e-buses.

The responsibility will accrue once the e-bus owner and the supplier or a third party in charge for battery maintenance, jointly conclude that a battery does not fulfil its intended function anymore and cannot be restored through conventional maintenance measures anymore (decommissioning decision).

Once one or more e-bus batteries cannot fulfil their intended functions anymore, they shall be extracted from the vehicles and managed in a safe and responsible manner in-line with the requirements specified in section [link to respective section, e.g. as specified in Box 11].

The supplier's responsibilities encompass all logistical, administrative, and financial aspects related to these tasks and shall be conducted in a timely manner and within [X] weeks after having been informed about the decommissioning decision. The supplier's responsibilities may be fulfilled through a third party assigned by the supplier, presupposing this entity can prove capability to conduct all related tasks with due care and in-line with given provisions.

The supplier shall give evidence that they have sufficient capacities to fulfil this requirement in [name of city and country] and guarantee availability for at least [12] years starting from the date of commissioning of the e-buses and batteries. This evidence may refer to adequate provisions made with a Producer Responsibility Organisation for vehicle-batteries that is registered as such in [name of country].

3.10 Measure 10: Encouraging battery reuse

What?	Encourage battery designs and business models that anticipate and intend battery reuse/repurposing after the first-life application in e-buses
Why?	Many aged batteries that are not suitable for powering e-buses any more can still be used in other applications. Such reuse or repurposing significantly extends the battery lifetimes.
Policy relevance	Medium: Policymakers can encourage reuse/repurposing strategies. This may be achieved through EPR policies (see measure 9) that entail mandatory targets for battery reuse and repurposing.

Measure 9 on decommissioning agreements can also be extended in a way suppliers are encouraged to already plan a second-life applications for the batteries in the production phase. While all considerations on circularity of e-bus batteries speak for second- or even third-life applications through reuse/repurposing (see section 2.4), there are various challenges reaching beyond the aspect of battery diagnostic data covered in Measure 7:

- Temperature management systems, protective housing and BMS are tailored to the needs of e-buses. Stationary applications require different design aspects.
- While it is theoretically possible to build batteries fulfilling design criteria for both, mobile and stationary applications ('design-for-reuse'), the second life phase lies some years in the future. A design-for-reuse will only yield tangible advantages to the producer, if a sufficient number of such batteries is given for reuse/repurposing in a defined geographic area (e.g., country), within a reasonable timeframe and to entities that cooperate with the producer.

Due to various uncertainties of future battery second-life markets, as well as the lack of clear design-for-reuse standards, only few companies currently embrace such design-for-reuse strategies[16].

In procurement, it can be considered to encourage such design-for-reuse. In specific, tender documents may take up this aspect as a non-mandatory criterion, where bidders that can credibly demonstrate to follow a design-for-reuse strategy are given extra credits and gain a better rating compared to bidders not convincingly responding to this aspect.

It is recommended to approach this aspect closely linked to requirements on EPR-based decommissioning agreements (Measure 9) and sound battery end-of-life management (Measure 11).

Box 10: Draft procurement text to encourage battery reuse

Suppliers are encouraged to design e-bus batteries in such a way that they can be reused/repurposed after their first life as e-bus batteries, and to integrate reuse/repurposing into their business model. Design strategies might involve (but might not be limited to) battery packs that can be transferred to other power storage applications without physical modification, and the use of battery management systems allowing interoperability with one or more common stationary applications. Related business models might involve (but might not be limited to) to efforts to take back used batteries with the intention of deploying them in second-life applications such as stationary power storage.

The supplier shall indicate whether he follows one or more such approaches and provide background explanations and underlying concepts, including links to relevant documents and websites. In addition, the supplier shall give background whether these initiatives

- Are applicable to the e-buses and batteries offered under this tender
- Are implemented or planned for the setting of [name of city and or country]

[16] Amongst others, Volvo is running tests on repurposing used e-bus batteries for stationary solar applications (Sustainable Bus 2020)

3.11 Measure 11: Sound battery end-of-life management

What?	Specifying key performance indicators to ensure that end-of-life management of batteries is conducted according to established good practices
Why?	To ensure that user and end-of-life batteries are managed according to ambitious circular economy requirements
Policy relevance	High: Sound management of e-vehicle batteries should ideally be regulated on a national level in a way that sub-standard processes and disposal pathways are banned and effectively sanctioned

Once e-buses or their batteries are decommissioned, it is important that this is conducted through experienced entities operating in line with international good practices related to health and safety, reuse and recycling. Basically, any end-of-life management partner taking over obsolete e-bus batteries should ensure the sequence of safe transport, testing, reuse and recycling as indicated in Figure 4. Nevertheless, there is no international standard defining sound Li-ion battery recycling. Hence, owners of e-buses aiming to decommission batteries have no clear guidance on how to identify sound operators. This can be overcome by describing key performance indicators in contract documents for the end-of-life management services (see Box 9).

It is important to consider that full-fledged Li-ion battery recycling is so far only established in a limited number of countries in Asia (e.g., China, Japan, S-Korea), Europe (e.g., Belgium, Finland, France, Germany) and N-America (e.g., USA) (Sojka et al. 2020). While recycling processes are also being set up in countries such as India, South-Africa, Costa Rica, Columbia and Brazil, many world regions still lack related capacities so that sound recycling will depend on shipments across international boundaries. Therefore, disposal contracts for used vehicle batteries may in some cases rely on companies specialised on international management of hazardous waste. It is noteworthy that such disposal contracts may be associated with net costs (also see section 2.3.4). Measure 9 gives some guidance on how these costs can be delegated to the producers of buses and batteries.

Box 11: Draft performance indicators for contracts on sound end-of-life management of vehicle batteries

The batteries shall be picked-up, transported and processed according to international good practices in all related fields, including fire safety, road safety and occupational health and safety.

All batteries shall undergo a state of health assessment with a view to determine their reuse/repurposing potentials. Batteries, battery modules and battery cells found suitable for reuse/repurposing shall be used accordingly.

Batteries, battery modules and battery cells found unsuitable for reuse/repurposing shall be recycled. Recycling is to be conducted in line with international good practices and with the aim to effectively prevent emissions of hazardous substances, recover embedded raw materials and reduce waste volumes for disposal.

The applied recycling processes shall at least achieve a recycling efficiency of 50% (at least 50% of the mass of the battery is recycled) and enable the recovery of copper, cobalt and nickel.

All conducted steps shall be conducted in full compliance with applicable national and international laws and regulations.

The operator taking over the batteries shall submit evidence for compliance with the requirements above. As a minimum, the operator shall provide the following documentation to the client:

- All licenses and permits as required by national law (to be provided prior to taking over the batteries).
- A certificate over sound management of all received batteries. The certificate should give clear information on the whereabouts of each battery or parts and fractions thereof, applied management processes and links to downstream operators who took over all or part of the generated materials (to be provided within 3 months from taking over the batteries).

Footnotes:

- The recycling efficiency of 50% is a value that is well achievable with current good practices. In Europe, more ambitious mandatory minimum values are planned (65% by end of 2025, 70% by end of 2030) and also combine this with material specific minimum recovery levels (e.g. 50% for lithium and 90% for cobalt, nickel and copper by end of 2027) (Council of the European Union 2023).
- The recovery of copper, cobalt and nickel is well established in current Li-ion battery recycling processes. In the future, lithium may be added to this list. Nevertheless, lithium recovery is not yet a standard practice.

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4 Further reading

The following references are considered useful material for planning measures around circularity of e-bus batteries.

	Type of publication	Content	Reference
Industrial Recycling of Lithium-Ion Batteries – A Critical Review of Metallurgical Process Routes	Scientific article	Detailed overview of existing recycling processes for Li-ion batteries and their specifications	(Brückner et al. 2020)
Comparative study of Lithium-ion battery recycling processes	Scientific report	Good overview on the current situation of Li-ion battery recycling, including aspects such as hazardous substances. Also good overview of major recycling players worldwide	(Sojka et al. 2020)
International Review on Recycling Ecosystem of Electric Vehicle Batteries	Report	Description of battery recycling ecosystems in various countries, including Germany, EU, California (US), China, Japan, and South Africa	(Bej et al. 2022)
Research on Technical Systems of Battery Electric Buses in China	Report	Analysis of challenges and solutions for e-bus purchase, supporting facilities, operation, maintenance and decommissioning in China	(Li et al. 2022)
Battery Ecosystem: A Global Overview, Gap Analysis in Indian context, and Way Forward for Ecosystem Development	Report	Analysis of numerous aspects around battery types, applications, standards, reuse, recycling etc. Main focus on India, but also with strong global perspective	(Mandal et al. 2022)
Second life batteries lifespan: Rest of useful life and environmental analysis	Scientific article	Provides an overview of battery reuse/repurposing concepts	(Casals et al. 2019)
A Study on the Safety of Second-life Batteries in Battery Energy Storage Systems	Report	Overview on state-of-play of EV battery repurposing and related safety considerations and standards	(Christensen et al. 2023)

Table 4 Overview of useful publications for further reading

Source: Own compilation

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List of References

Aamodt, A.; Cory, K.; Coney, K. (2021): Electrifying transit: A guidebook for implementing cattery electric buses, 2021. Online available at https://www.nrel.gov/docs/fy21osti/76932.pdf, last accessed on 13 Mar 2023. Figure 2 1: The 5-step waste hierarchy

avicenne energy (2019): The Rechargeable Battery Market and Main Trends 2018-2030, 2019. Online available at https://rechargebatteries.org/wp-content/uploads/2019/02/Keynote_2_AVICENNE_Christophe-Pillot.pdf, last accessed on 13 Jul 2022.

Ayetor, G. K.; Quansah, D. A.; Adjei, E. A. (2020): Towards zero vehicle emissions in Africa: A case study of Ghana. In: Energy Policy 143, p. 111606. DOI: 10.1016/j.enpol.2020.111606.

Battery University (2021): Types of Lithium-ion. Online available at https://batteryuniversity.com/article/bu-205-types-of-lithium-ion, last updated on 22 Oct 2021, last accessed on 24 Nov 2022.

Bej, S.; Zhimomi, T.; Hochfeld, C.; Riehle, E.-B.; Rather, Z.; Bradiya, M. R.; Maity, S. (2022): International review on Recycling Ecosystem of Electric Vehicle Batteries. New Delhi, 2022. Online available at https://changing-transport.org/publications/review-recycling-ecosystem-electric-vehicle-batteries/, last accessed on 8 Dec 2022.

BMU & UBA (2011): Environmentally Sound Alternatives in Mobile Air Conditioning. Federal Ministry for the Environment, Nature Conversation and Nuclear Safety (BMU) and Federal Environment Agency (ed.), 2011. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/419/dokumente/factsheet_mobile_air_conditioning1.pdf, last accessed on 7 Dec 2022.

Brückner, L.; Frank, J.; Elwert, T. (2020): Industrial Recycling of Lithium-Ion Batteries—A Critical Review of Metallurgical Process Routes. In: Metals 10 (8), p. 1107. DOI: 10.3390/met10081107.

California Code of Regulations (2022): Final Regulation Order, Section 1962.6, Title 13, California Code of Regulations, 2022. Online available at https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/2acciifro1962.6.pdf, last accessed on 19 Jan 2023.

Casals, L. C.; García, B. A.; Canal, C. (2019): Second life batteries lifespan: Rest of useful life and environmental analysis. In: Journal of Environmental Management (232), pp. 354–363. Online available at https://doi.org/10.1016/j.jenvman.2018.11.046.

Christensen, P. A.; Mrozik, W.; Wise, M. S. (2023): A Study on the Safety of Second-life Batteries in Battery Energy Storage Systems. Office for Product Safety & Standards (ed.), 2023. Online available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1133213/safety-of-second-life-batteries-in-bess.pdf, last accessed on 10 Feb 2023.

Council of the European Union (2023): Proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. Interinstitutional File: 2020/0353(COD). Brussels.

DERA (2022): Rohstoff Preismonitor Oktober 2022, 2022. Online available at https://www.deutsche-rohstoffagentur.de/DERA/DE/Aktuelles/Monitore/2022/10-22/2022-10-preismonitor.pdf;jsessionid=2AEB7988FE0404ED8EC9B6190FFCF684.2_cid321?__blob=publicationFile&v=3, last accessed on 24 Nov 2022.

Enel X (2023): Trasporto elettrico pubblico: le soluzioni | Enel X. Available online at https://www.enelx.com/it/it/istituzioni/trasporto-elettrico/elettrificazione-urbana/trasporto-pubblico, updated on 4/18/2023, checked on 4/18/2023.

Electrive.net (1 Apr 2022): Gotion High-Tech baut LFP-Zellen mit 210 Wh/kg in Serie, 1 Apr 2022. Online available at https://www.electrive.net/2022/04/01/gotion-high-tech-baut-lfp-zellen-mit-210-wh-kg-in-serie/, last accessed on 30 Nov 2022.

European Commission (2015): Circular Economy Package: Questions & Answers. Online available at https://ec.europa.eu/commission/presscorner/detail/en/MEMO_15_6204, last accessed on 23 Nov 2022.

European Commission (2020): Proposak for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020, 2020.

European Union (2000): Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles, 2000.

European Union (2006a): Directive 2006/40/EC of the European Partliament and of the Council of 17 May 2006 relating to emissions from air-conditioning systems in motor vehicles and amending Council Directive 70/156/EEC, 2006. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0040&from=EN, last accessed on 8 Dec 2022.

European Union (2006b): Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, 2006.

Fuller, R.; Landrigan, P. J.; Balakrishnan, K.; Bathan, G.; Bose-O'Reilly, S.; Brauer, M.; Caravanos, J.; Chiles, T.; Cohen, A.; Corra, L.; Cropper, M.; Ferraro, G.; Hanna, J. et al. (2022): Pollution and health: a progress update. In: The Lancet. Planetary health 6 (6), e535-e547. DOI: 10.1016/S2542-5196(22)00090-0.

Gao, Z.; Lin, Z.; LaClair, T. J.; Liu, C.; Li, J.-M.; Birky, A. K.; Ward, J. (2017): Battery capacity and recharging needs for electric buses in city transit service. In: Energy 122, pp. 588–600. DOI: 10.1016/j.energy.2017.01.101.

Henning, M.; Thomas, A. R.; Smyth, A. (2019): An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for BatteryTemperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric BusesElectric and Fuel Cell Electric Buses, 2019. Online available at https://www.sustainable-bus.com/wp-content/uploads/2019/12/electric-bus-range-cold-weather.pdf, last accessed on 24 Nov 2022.

Li, C.; Wu, Z.; Li, W.; Mu, K. (2022): Research on Technical Systems of Battery Electric Buses in China, 2022. Online available at https://transition-china.org/wp-content/uploads/2022/12/Research-on-Technical-Systems-of-Battery-Electric-Buses-in-China-4.pdf, last accessed on 10 Jan 2023.

Mandal, A.; Dikshit, C.; Singha, H.; Parihar, A.; Tripathy, A.; Mohapatra, P. (2022): Battery Ecosystem: A Global Overview, Gap Analysis in Indian context, and Way Forward for Ecosystem Development. New Delhi, 2022. Online available at https://changing-transport.org/wp-content/uploads/GIZ_Battery-ecosystem-report.pdf, last accessed on 30 Jan 2023.

Manhart, A.; Betz, J.; Schleicher, T.; Hilbert, I.; Smit, R.; Jung, H.; Adogame, L.; Olagunju, I.; Clews, A.; Adegun, O. (2022): Management of End-of-life Li-ion Batteries through E-waste Compensation in Nigeria, 2022. Online available at https://prevent-waste.net/wp-content/uploads/2022/05/Management-of-End-of-life-Li-ion-Batteries-through-E-waste-Compensation-in-Nigeria_Feasibility-Study_ECoN.pdf, last accessed on 2 Dec 2022.

MassTransit (2015): BYD Announces 12 year Battery Warranty. Online available at https://www.masstransitmag.com/home/press-release/12058920/byd-motors-llc-byd-announces-12-year-battery-warranty, last accessed on 13 Mar 2023.

McGuffie, M. (2021): Driving the Shift to Electric Buses in Hot Climates - Battery Electric Buses in the Phoenix Metropolitan Area, 2021. Online available at https://www.azta.org/images/uploads/event-files/Driving_the_Shift_to_Electric_Buses_in_Hot_Weather_Climates_VM_PDF.pdf, last accessed on 24 Nov 2022.

Miaja, G. G.; Acevedo, H.; Leticia, C. J. (2022): Análisis del monitoreo de desempeño de autobuses eléctricos en la ciudad de México, 2022. Online available at https://theicct.org/wp-content/uploads/2022/12/Mexico-hvs-ZEBRA-analisis-desempeno-buses-electricos-cdmx-dec22.pdf, last accessed on 7 Dec 2022.

Poworks (2020): A Comparison of NMC/NCA Lithium ion Battery and LFP Battery - Poworks. Available online at https://poworks.com/a-comparison-of-nmc-nca-lithium-ion-battery-and-lfp-battery, updated on 7/28/2022, checked on 4/18/2023.

Prevent & StEP (2022): Practical Experiences with the Basel Convention: Challenges, Good Practice and Ways to Improve Transboundary Movements of E-Waste in Low and Middle Income countries, Discussion Paper, 2022. Online available at https://prevent-waste.net/wp-content/uploads/2022/04/PREVENT-StEP_Practical_Experiences_Basel-Convention_discussion-paper-2022.pdf, last accessed on 7 Dec 2022.

Report Linker (2021): Electric Bus Market, 2021. Online available at https://www.reportlinker.com/p06180080/Electric-Bus-Market.html?utm_source=GNW, last accessed on 24 Nov 2022.

Slattery, M.; Dunn, J.; Kendall, A. (2021): Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review. In: Resources, Conservation and Recycling 174, p. 105755. DOI: 10.1016/j.resconrec.2021.105755.

Sojka, R.; Pan, Q.; Billmann, L. (2020): Comparative study of Lithium-ion battery recycling processes. ACCUREC Recycling GmbH (ed.), 2020. Online available at https://accurec.de/wp-content/uploads/2021/04/Accurec-Comparative-study.pdf, last accessed on 2 Dec 2022.

Sustainable Bus (2020): Volvo Buses, the focus on reuse of bus batteries. A cooperation with Batteryloop. 14.09.2020, 2020. Online available at https://www.sustainable-bus.com/news/reuse-bus-batteries-volvo-buses-batteryloop-stena-recycling/, last accessed on 16 Feb 2023.

UNECE (2022): United Nations Global Technical Regulation on In-vehicle Battery Durability for Electrified Vehicles, 2022. Online available at https://unece.org/sites/default/files/2022-04/ECE_TRANS_180a22e.pdf, last accessed on 10 Jan 2023.

Wunderlich-Pfeiffer, F. (12 Oct 2022): Die Revolution der Natrium-Akkus wird absehbar. In: golem.de. 2022, 12 Oct 2022. Online available at https://www.golem.de/news/akkutechnik-die-revolution-der-natrium-akkus-wird-absehbar-2210-168344.html, last accessed on 19 Oct 2022.

Zhu, J.; Mathews, I.; Ren, D.; Li, W.; Cogswell, D.; Xing, B.; Sedlatschek, T.; Kantareddy, S. N. R.; Yi, M.; Gao, T.; Xia, Y.; Zhou, Q.; Wierzbicki, T. et al. (2021): End-of-life or second-life options for retired electric vehicle batteries. In: Cell Reports Physical Science 2 (8), p. 100537. DOI: 10.1016/j.xcrp.2021.100537.