Resource-Efficient Battery Life Cycles

Circular Economy Initiative Deutschland

Driving Electric Mobility with the Circular Economy

acatech/Circular Economy Initiative Deutschland/SYSTEMIQ (Eds.)

SYSTEMIQ

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NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

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Reading guide for this report

This report is the **result of discussion and cooperation** of the "Traction batteries" working group of the *Circular Economy Initiative Deutschland.* The initiative is coordinated by acatech – National Academy of Science and Engineering in cooperation with SYSTEMIQ.

The present report thus represents the **joint expertise and positions from science, business and civil society** and **corresponds to the acatech guidelines** of a science-based, independent, neutral, and public-interest oriented consultancy for politics and civil society.

The **summary** provides a condensed overview of the findings of the report. The **executive summary,** which is published separately, summarises this further for decision-makers. The **main part** of the report examines a Circular Economy for traction batteries more closely and includes several **in-depth studies** on focus topics as well as further recommendations of the working group. **The structure of the report** is outlined in Chapter 1, Introduction of the General Report. The **glossary** contains definitions of key topics and should therefore be considered an important part of the report.

The report also contains extracts from a **material flow analysis by the Wuppertal Institute.** This quantifies the possible effects of Circular Economy measures for traction batteries. This analysis was carried out independently of the work of the Traction Batteries working group but is quoted here for the sake of completeness.

The **annex** contains the pilot topic reports of the sub-working groups, an overview of the **members and structure of the working group,** and a description of the employed **methodology.**

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Summary

Between October 2019 and May 2020, the Traction Batteries working group of the *Circular Economy Initiative Deutschland* developed a roadmap to achieve a Circular Economy for traction batteries. **The members of the working group are representatives from leading academic institutions, German companies, and associations with proven expertise on traction batteries and thus covering the entire value chain of traction batteries:** from production (battery material, production equipment, batteries, and vehicles) and logistics to recycling and metallurgy to software applications and systemic integration. The working group was thus able to achieve its goal of ensuring a holistic approach to the topic.

This report is the central result of the work of the Traction Batteries Working Group. It includes the discussion of the **potentials, obstacles, and possible conflicting objectives** of a Circular Economy for traction batteries. In addition, it also outlines a **vision**, develops **three pilot projects** to accelerate the transformation, and derives **recommendations for action** for the central actors. The members thus support the initiation and long-term anchoring of the Circular Economy in Germany and beyond.

Background – the Circular Economy for traction batteries is indispensable

I. **Timely decarbonisation of the transport sector is essential for achieving the Paris climate targets. In addition to a general reduction in the volume of traffic and an increase in multi-modal mobility offers, the rapid scaling of the number of battery electric vehicles for individual transport is of central importance.** Even under today's conditions, after only 50,000[1, 2] – 80,000[3] kilometres driven, they have a better carbon footprint than vehicles with classic combustion engines. In addition to the increased use of renewable energies in the production and use of vehicles, Circular Economy measures can contribute to further reducing the carbon footprint of battery production, including materials. In accordance with the scenarios of the National Mobility Platform, Germany's goal is to have approx. seven to ten million electric vehicles in Germany by 2030.[4, 5] Battery electric vehicles will probably make up the vast majority of the car population in the long term.[6, 7] It is therefore necessary to accelerate their market breakthrough and to make them socially acceptable and environmentally friendly.

II. **Circular Economy measures further improve the environmental and economical performance of electric vehicles and can also create additional added value such as cost savings, job security, and increased economic resilience. Closing the loop thus makes a significant contribution to achieving the Paris climate goals and decoupling resource use from prosperity.** In particular, the Circular Economy includes productivity-enhancing multiple use, lifetime extension (repair and refurbishment), and effective and efficient recycling. These measures promise a significant improvement in the environmental performance of traction batteries (e.g. in the form of up to 40% reduction in CO_2 emissions over their service life)[8] and resource decoupling. In the short and medium term, they will also be able to secure and accelerate the market ramp-up of electric mobility. A Circular Economy could provide up to about 10% of the demand for important battery materials in 2030 (up to 40% by 2050)[9] and reduce net costs by up to 20% over the life cycle of the batteries.[10] The Circular Economy will further contribute to a more resilient economy and minimise dependency on materials imports, not only by tapping secondary material sources within the country but also by supporting economic models that can be exported. Current regulatory measures and existing conditions (e.g. low recovery quotas not differentiated according to material) do not sufficiently support the effective closed-loop recycling of important battery materials and must therefore be modified. As can be seen: We are at the beginning of a new economic paradigm in which the product life cycle must be planned before and during product development and manufacturing. In order to fully utilise the potential of such

1 | See Regett et al. 2019.
2 | See Regett 2019.
3 | See Agora Verkehrswende 2019.
4 | See Nationale Plattform Zukunft der Mobilität 2020.
5 | Including hybrid vehicles and pure battery electric vehicles
6 | See International Energy Agency 2019.
7 | Fuel cell vehicles will also contain lithium-ion batteries to ensure the driving dynamics and long service life of the fuel cell.
8 | See World Economic Forum 2019.
9 | See Buchert et al. 2019.
10 | See World Economic Forum 2019.

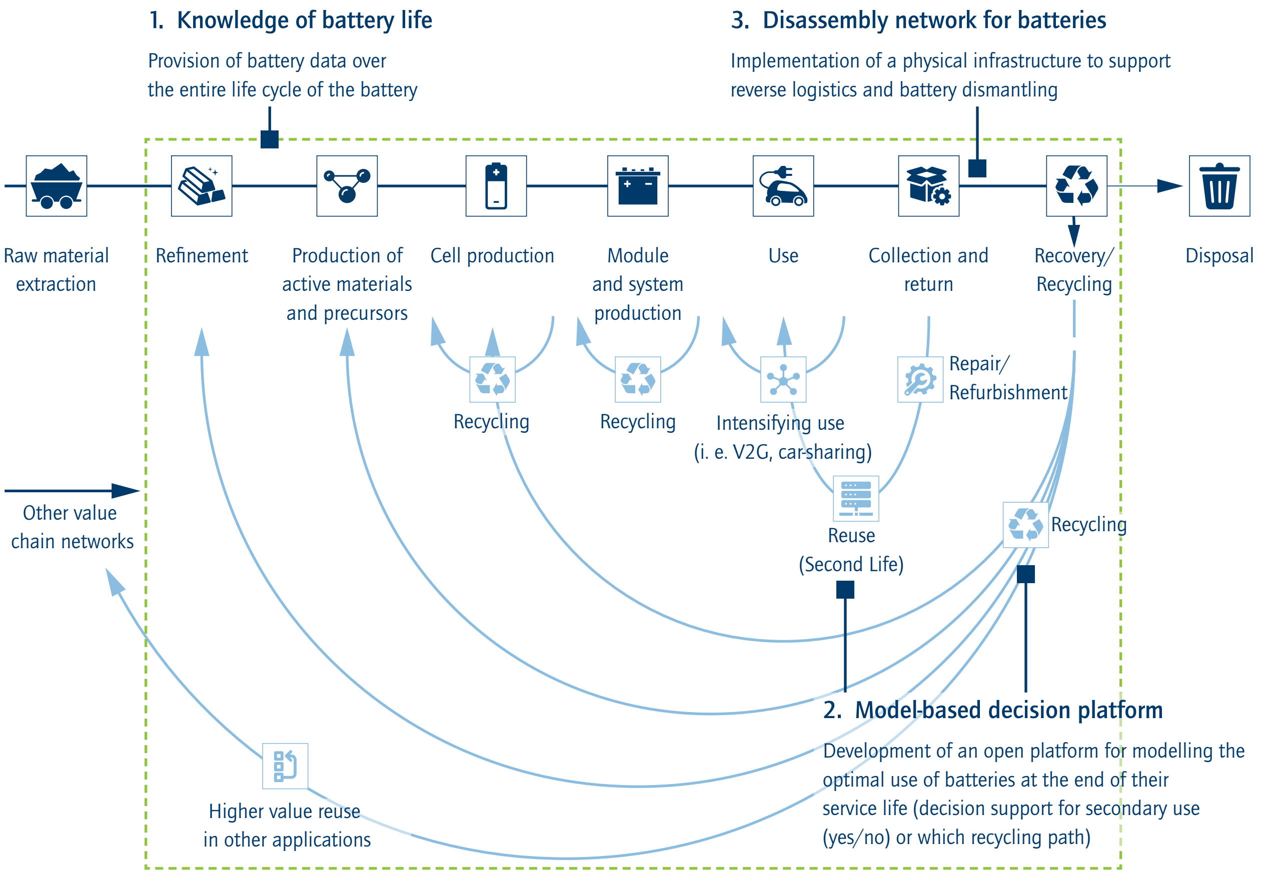

Figure 1: Illustration of the Circular Economy for traction batteries and scope of the Traction Batteries Work Group. Items 1 to 3 locate the pilot topics along the value chain (Source: own representation, based on the representation of the World Economic Forum 2019)

an economic form, decisive action is needed as these new value networks start to emerge in order to create the right incentives, technologies, and framework conditions.

III. **An analysis carried out by the Wuppertal Institute, including quantification of the possible effects of Circular Economy levers on material flows of traction batteries, shows considerable potential for reducing material requirements and greenhouse gas (GHG) emissions:**[11] Based on the assumptions made there, by 2030, 8,100 tonnes of lithium, 27,800 tonnes of cobalt, and 25,700 tonnes of nickel could be recovered from vehicles placed on the German market. According to current prices (as of April 2020), this would correspond to approx. €1.2 billion. The amount of lithium would correspond to 10 times the amount in traction batteries in Germany in 2020. If the batteries were recycled in Germany, according to the calculations made here – based on recognised environmental effect databases – this would result in cumulative energy savings of 308 petajoules by 2050. This corresponds to the primary energy consumption of the city of Hamburg in 2019. The modelling thus supports the statements made by other renowned actors such as the EU Joint Research Centre, the Ellen MacArthur Foundation, Material Economics, and, in particular, the UN International Resource Panel: Circular Economy measures have great potential to significantly improve the footprint of industrial products such as traction batteries, to increase import independence of key battery materials, and to create economic value. Detailed results of a material flow analysis of Circular Economy measures can be found in Section 2.2 and Annex H of the report.

11 | See Wuppertal Institute [forthcoming].

IV. **The extensive use of digital technologies is necessary to enable the circular management of traction batteries, including the necessary data transparency**. Among other things, digital technologies help to generate business model-relevant data about the life cycle of the batteries (in particular, static data such as origin and environmental footprint and dynamic data such as remaining capacity or location data), share it between relevant actors, and maximise corporate and societal benefits. For the first time, digital technologies are enabling real end-to-end transparency on value losses and potentials of the new mobility and resource paradigm, which also includes ACES (autonomous, connected, electric, shared) mobility. Finally, digital technologies increasingly enable automated circular measures (e.g. end-of-life tracking, automated dismantling, remanufacturing, and recycling) and thus a more cost-effective, higher quality product and material (re)use. The *Circular Economy Initiative Deutschland* therefore focuses not only on the material Circular Economy but also on the relevance of digital technologies for an information-driven Circular Economy.

Fundamental considerations – maxims for successful transformation

V. **The task of the Circular Economy is to implement a fundamental transformation in the entire economy in the medium term. In this context, traction batteries can be seen as a prototypical example from which lessons can be learned for the overall transformation of the economy.** Several challenges must be overcome for a successful transformation. Nevertheless, it promises great opportunities for generating social value and cohesion. To this end, new collaborations between actors and a "business as unusual" mind-set are also required.

This transformation is not simply "nice to have" but rather necessary in order to secure the supply of raw materials for the economy, to meet climate targets, and ultimately to preserve our livelihood. The advantages of the Circular Economy can provide effective incentives for the companies concerned

Area	from ...	to ...
Competition	Competition	"Coopetition": Collaborative business models
Understanding of value	Value defined by short-term monetary success	Long-term, holistic (economic - environmental – societal) creation of value
Incentives	Waste disposal by Extended Producer Responsibility	Life cycle management through producer ownership
Flow of information	Fragmented commodity markets	Platform considering transparent, eco-social principles
Use of resources	Optimisation for fast linear product throughput and thus material throughput	Holistic value maximisation through focus on productivity and value preservation
Basis of value creation	Mass production	Smart use of information

Figure 2: Circular Economy means an economic transformation in many areas (Source: own representation)

to act in a self-motivated manner. Further regulatory incentives are to be designed by the legislator. Decisive action is needed now in order to make the transformation possible. The working group provides central actors from politics, business and science with fundamental considerations and impulses for this purpose, as well as practical approaches for possible short-term action (pilot projects) and recommendations for action within the framework of a roadmap.

VI. **It is important to consider a systemic integration of the Circular Economy transformation when addressing future issues – for example, the ambitious expansion of renewable energies, the harmonisation of European electricity markets, and the development of multi-modal electromobility.** Only in this way can productivity gains be achieved in the economy as a whole. The members of the working group expressly support a systemic approach. In Section 3.1, Basic Assumptions of the General Report, 10 basic recommendations and positions of the Traction Batteries Working Group are presented.

VII. **The members of the working group support 10 guiding principles for sustainable batteries of the Global Battery Alliance.** These include the Circular Economy for batteries and cover:

- the productive and safe use of batteries – as a contribution to achieving the Paris Climate Targets
- the assurance transparency, energy efficiency, sector coupling, and use of renewable energies
- the focus on the creation of good jobs worldwide
- the unconditional respect of human rights and orientation towards the UN sustainability targets. After all, the Circular Economy is not an end in itself but rather has the clear goal of harmonising eco-social and economic optimisation. The members of the *Circular Economy Initiative Deutschland* expressly support this.

VIII. **Regulatory and incentivising measures initiated by the German government, institutions of the European Union, and transnational corporate collaborations are essential for creating an effective market environment for the Circular Economy of batteries.** These include fair business conditions (level playing fields) for the economic actors through harmonised legislation, clear definitions, uniform standards, and (IT) infrastructure as well as incentives for the return and high-quality reuse or recycling of traction batteries. These measures should address various points of intervention in the Circular Economy. This spans incentives for product and system design for circularity, the embedding of traction batteries in resource-producing ecosystems during use, assurance of a high collection rate at the end-of-life (EoL), and the **description of meaningful definitions and binding high recovery rates**. Especially the latter, the high collection and recovery rates, play an important role in achieving closed loops. The working group therefore makes specific, ambitious recommendations based on the shared technical expertise, which can be implemented in practice. These take into account the results

Material	Recommended Recovery rates*	
	2025 – binding	2030 – to be aspired to***, ****
Total battery**	60 %	70 %
Lithium	50 %	85 %
Cobalt	85 %	90 %
Nickel	85 %	90 %
Copper	85 %	90 %
Steel	90 %	95 %
Aluminum (without Al foil)	90 %	95 %

* is determined over the entire recycling process excluding collection or return (see Figure 26 in the general report), in battery quality or comparable. The recovery of organic components should be designed to optimise the exergy of the overall process and only secondarily according to mass yield and not at the expense of the recovery of high-quality recyclates of the important battery materials. Return losses must be accounted for additionally and minimised accordingly.

** The proposed recovery rates for the total battery should be set flexibly because organic and volatile substances (electrolyte, plastics, graphite) account for a significant proportion (about 30–40%). These can often not be recovered in adequate quality or only at great cost, which could be at the expense of the energy balance and yield of important battery materials. Because the latter are given priority, strict minimum values for the entire battery or individually for electrolyte, plastics, and graphite are unlikely to be considered appropriate. Their recovery should only be aimed at by ensuring the overall energy balance and recovering important battery materials in high quality.

*** In the view of Agora Verkehrswende and the Oeko-Institut, under regulatory premises and for reasons of investment security, it is preferable to also make the values for 2030 binding and, if necessary, to subject them to revision.

**** Based on work for the European Commission in preparation for the revision of the EU Battery Directive, the Oeko-Institut believes that more ambitious 5% higher values for cobalt, nickel, and copper for 2025 and 2030 are achievable in terms of industrial best practice. These values should be checked regularly and, depending on technical progress, also be adapted in the legal requirements.

Table 1: Recommendations of the Traction Batteries Working Group on recovery rates to be made mandatory or to be aimed at (taking into account the related definitions)

of the entire recycling process – from the dismantling of the batteries to the output of metallurgical processing to high quality target materials (avoidance of downcycling). Both the optimisation of material yields and energy consumption are considered. **The recommended values must therefore be understood in the context of the system limits, definitions, and further explanations set out here** (see in-depth study on battery recycling).

Also and especially the provision of business-relevant information over the life cycle must be considered. In this way – and only in this way – the Circular Economy can not only strengthen Germany as a business location but also become the next export hit: "Made WITH Germany".

IX. **Implementation must be embedded in the European context, in particular in the European Green Deal (EGD)**. These include, in particular, the European Commission's plans for the creation of product passports within the framework of the "European Data Spaces", the amendment of relevant regulations (e.g. the Battery Directive and the regulation of cross-border transport) and other relevant activities. Only through integration into the European framework and "green" stimulus packages can a Circular Economy be successfully implemented in Germany and sustainable battery value chain be possible.

In-depth study I: Covid-19 and Circular Economy for traction batteries

By September 2020, the Covid 19 pandemic had claimed over 800,000 lives worldwide. The effects of the virus have been and continue to be severe: Apart from health aspects (the care of the sick, the measures needed to combat the spread of the virus, and the development of medicine and vaccines) and restrictions in public and social life, the pandemic led to probably the biggest recession of the last century. In response, trillion-dollar economic stimulus packages have been launched worldwide, including by Germany and the European Union.[12]

Commissioner Frans Timmermans stresses that the response to the Covid 19 crisis must be an integral part of the European Green Deal.[13] Appropriate investment programmes **should be geared to the transformation towards a sustainable economy** – for example in Battery Electric Vehicles (BEV), renewable energies, a climate-friendly infrastructure[14] – and a Circular Economy. Because of the essential contribution of resource use to climate change and the threat to planetary boundaries, it is essential to decouple prosperity from resource use. The Circular Economy is necessary for this and therefore also without alternative.[15] Decisions taken now will strongly influence the path of greenhouse gas emissions and resource use for the next decade.

Support packages must therefore be made compatible with the ambitious transformation path towards a climate-friendly Circular Economy.

This report from the Traction Batteries Working Group shows that **the Circular Economy provides clear long-term macroeconomic and specific benefits for traction batteries,** by increasing productivity, resilience, import independence, and employment security. For companies, similar benefits can be achieved through measures such as cost reductions, new business models, and better supply chain risk management. However, in order **to utilise these potentials, considerable targeted intervention is still required.**

The Covid 19 crisis also illustrates the target picture and transformation path proposed here: Serious changes in our way of life are possible, and selective measures that appear unusual may be appropriate. This would allow the testing and scaling up of new business models and value chain structures that would otherwise be legally impossible, too risky (for reasons of economic efficiency or antitrust concerns), or unprofitable. **Experiences from the response to Covid-19 should therefore be assessed in terms of their transfer to the transformation to a Circular Economy.**

The results of the traction batteries working group can also – or especially – in times of the Covid 19 crisis serve to enable first steps towards the transformation towards a climate-friendly, resource-decoupled Circular Economy for traction batteries.

12 | See Nienaber/Wacket 2020.
13 | See Europäisches Parlament 2020.
14 | See Energy Transitions Commission 2020.
15 | See International Resource Panel 2020.

Seizing the opportunity – vision of a Circular Economy for traction batteries and the way to get there

X. **The working group has developed a common vision for the Circular Economy for traction batteries**. This describes what a German Circular Economy for batteries could look like in 2030 along the five dimensions of regulatory system, material flows, technical development, value networks, and internal implementation.

The goal is to enable all participants to develop a common vision of the Circular Economy and to align measures and success with it.

XI. **By developing recommendations for action for politics, industry, and the scientific community, and prioritising them over time, the** Circular Economy Initiative Deutschland **creates a roadmap for achieving the vision.**

This is accompanied by the working group's call to decision-makers to take action in their own field as well as in cooperation with the other actors. The detailed recommendations for action can be found in Chapter 5.

As a central actor, the German legislator is called upon to provide ambitious incentives in the European process. In both the European and national context, the range of resource policy instruments (i.e. economic, regulatory, and informational as well as education and research) should be used to accelerate the transformation towards a Circular Economy.

The members of the Traction Batteries Working Group and the office of the *Circular Economy Initiative Deutschland* offer to support this process with their expertise.

XII. **By working on the three pilot profiles, the Traction Batteries Working Group has identified topics of central importance and outlined specific possible concrete implementation steps in order to accelerate the transformation.** The following core statements summarise the fundamental relevance of the respective pilot topic for the successful implementation of circular battery value chain **(see profiles, Chapter 4 in the General Report and Annex in the General Report for more detailed results)**:

1. **Pilot profile "Understanding the service life of the battery"** (Objective: systematic provision of battery data (data availability) over the entire life cycle of the traction battery.)

   - The use of data and information from battery life cycles plays a central role in initiating and implementing cross-company and supply chain collaboration. Increased data transparency can clarify ecological (decarbonisation) and social (responsible sourcing) target parameters and increase the economic use potential of batteries (efficiency and availability of raw materials) over their entire life cycle.
   - The members of the working group make proposals on effects, content, and incentives for relevant actors and structural conditions in the implementation. A central insight: Because, in principle, a lot of data on the condition of a battery is already present, but mostly not available, a major challenge is to create incentives for all actors involved to share data. In particular, the availability of vehicle manufacturers' data on initial use and the corresponding battery behaviour as well as on the location of the battery at the end of the (initial) use phase have been identified as key points. In this respect, incentives for vehicle manufacturers and users/owners to provide operating data (taking into account data protection) must be increased.

2. **Pilot profile "Model-based decision-making platform"** (Objective: to provide a basis for decision making using an open platform to model the optimal use of batteries at the end of their life cycle.)

   - Model-based decision support contributes to optimised decision making (second life or different recycling routes) for the treatment of used traction batteries. The goal is the overall optimised design of the battery life cycle and a fair distribution of expenses and revenues among the network of actors.
   - The members outline the basic conditions of such a tool as well as added value and incentives for the actors involved. A key statement: Model-based decision support must be based on real, validated data and take into account exergy losses and achievable output qualities in the various options for managing traction batteries after the end of their first life in a vehicle.

Regulatory framework

- Knowledge about the **whereabouts, condition, and eco-performance** of batteries while maintaining data protection and security
- **Uniform international standards** for EoL treatment and logistics
- EU-wide harmonised regulatory framework, including **incentives** for responsible sourcing, high value reuse, and responsible recycling
- **Level playing field** for participating actors through new edition of the EU Batteries Directive
- **Standardised method** for the determination and crediting of recyclates

Material flows

- Development of **tools** for tracking and eco-social decision making (e.g. **battery passports**, data spaces, LCA simulations)
- **Secure databases** with standardised interfaces and transparent protocols
- Clarity as to what extent **V2X and second life applications** of traction batteries are economically and environmentally reasonable
- **Collection and high-quality recycling (if suitable after Second Life) of all traction batteries** at the end of their service life
- **Post-consumer recyclates** represent a small (~10%) but growing part of the demand for key battery materials

Technological development

- **Design for circularity**/design for recycling and modularity are industry standard
- **Digital industry standardisation** and smart manufacturing (Industry 4.0, AI, IoT, Blockchain) flexibly support manufacturing and EoL management
- **Reliable provision of information through digital technologies** (e.g. Battery Passports, Digital Twins)
- **Increasing automation of maintenance and disassembly** resulting in cost savings and safety
- **Advanced recycling technologies** with high performance

Value networks

- **Decarbonisation of used materials** is a **strategic component of** the business of product manufacturers
- **Value creation increasingly collaborative** and across (several) life cycles of the battery
- **Management of batteries** across actors and the entire life cycle (cradle to cradle)
- **New roles** of existing actors and new market participants
- Proliferation of **digital platforms**
- **Strategic and operational integration** of the energy and transport sector in terms of sector coupling

In-house implementation

- **Efficient and safe handling** of the rapidly increasing quantities of EoL batteries **through effective disassembly networks (disassembly, assessment, transport)**
- **Application of new B2B/B2C business models** for circular product management
- Widespread use of **new economic indicator systems** (especially accounting)
- **Resource productivity** of the still expensive traction batteries is optimised by many actors (Ride-sharing and pooling, V2X)

Figure 3: Vision of the working group for a Circular Economy for traction batteries (Source: own representation)

Pilot projects ▶ **2021–2024: Short-term "lay the foundation"**

Public Policy

1. Definition of clear and mandatory **definitions and standards** (e.g. CO_2, human rights) while also maintaining data protection and security
2. Clarification of the **rights and duties** of all actors, for example in the matters of occupational health and safety, end-of-waste obligations, reporting, and the launch of **incentive systems** (e.g. deposit system for materials)
3. Establishment of a **central institutional** actor responsible for promoting the transformation
4. Ensuring **training and further education**

Business

5. Collaborative initiation of joint **(minimum) standards** for process chains and system design with the aim of establishing systemic designs for circularity
6. Establishment of **industry-wide agreements** for indicators, for example to **measure circularity** (economic, environmental, social and interactions thereof) as well as security-related aspects
7. Assurance that professionals are **trained** in EoL management for traction batteries

Science

8. Scientifically informed contribution to establishing generally accepted **key indicators, measuring quantities, and methods**
9. Technical and transdisciplinary **foundational research** focusing on supporting the optimisation of overall systemic effects
10. Provision of **academic training** for the circular economy

Pilot projects ▶ **By 2027: Medium-term "establish a structure"**

Public Policy

11. **Measures to increase transparency** in the industry and for their consumers and their technical implementation through Battery Passport and Data Spaces, such as standardised labelling to show environmental footprints
12. Scaling of **economic and scientific support** for relevant technologies, business models, and knowledge
13. **Harmonisation** of national and transnational regulations

Business

14. Provision of **relevant information** and data among relevant actors, for example by using **digital technologies** such as product passports
15. Development and scaling of **circular business models** that increase productivity beyond the recycling of old batteries
16. Scaling of investments for the circular economy, including **investment** in infrastructure for the collection and management of EoL batteries and digital technologies

Science

17. **Practical research and development,** particularly for new interdisciplinary solutions to optimise overall systemic effects

Pilot projects ▶ **By 2030: Long-term "breakthrough"**

Public Policy

18. Implementation of **sanctions** for failure to comply with existing requirements
19. **Consideration of the systemic potential** of traction batteries over the course of the energy turnaround (through simulations and big data analyses)
20. Application of measures to the **global context** for both main markets (race to the top) and developing economies (collaboration for development)

Business

21. **Planning that takes into consideration systemic resource and energy efficiency monitored throughout the value chain (entropy/exergy) as a measure of circularity**
22. Development of a Europe-wide infrastructure for the disassembly and recycling of traction batteries returning to the end of their life

Science

23. Provision of **methods and tools** for the assessment of energy and materials flows and their effects as well as business models, without the need for specialised technical knowledge

Figure 4: Roadmap of the Traction Batteries Working Group based on a synthesis of the recommendations for action (see chapter 5) (Source: own presentation)

3. **Pilot profile "Dismantling network for traction batteries"** (Objective: Outline a "project plan" for the implementation of a European dismantling network.)

   - The establishment of a Europe-wide network of efficient dismantling facilities for traction batteries is essential for the success of the entire recycling or reuse chain. After all, it is an important link between collection (e.g. authorised workshops) and further treatment/recycling (or Second Life) of the battery modules.
   - The members of the working group describe the conditions to be considered for the safe and efficient handling of end-of-life (EoL) traction batteries, the relevant (industry) standards, and the necessary steps towards a pan-European dismantling network. Central to this is that investment decisions for new dismantling facilities must be made on a well-founded data basis with regard to timing, choice of location, dimensioning of the facility in line with future growth in return volumes, and specification of the facility equipment (degree and adaptability of automation with regard to changing battery formats and chemistries). In this way, the recycling infrastructure can be precisely improved and made scalable on a European scale. There is also an urgent need to establish standards, especially for the safe handling of potentially hazardous battery systems, as well as to ensure the associated training of specialist personnel.

By developing exemplary roadmaps, the pilot topics should also facilitate the rapid implementation of the Circular Economy. In addition, the interactions between the pilot profiles were discussed, and corresponding interfaces were defined (see Figure 9). The profiles thus contain more in-depth, topic-specific knowledge and recommendations for action on the work of the traction battery working group.

XIII. **Open questions remain, and further cooperation and research as well as development are necessary to clarify them. Civil society also has an active role to play**. In particular, the following issues were highlighted:

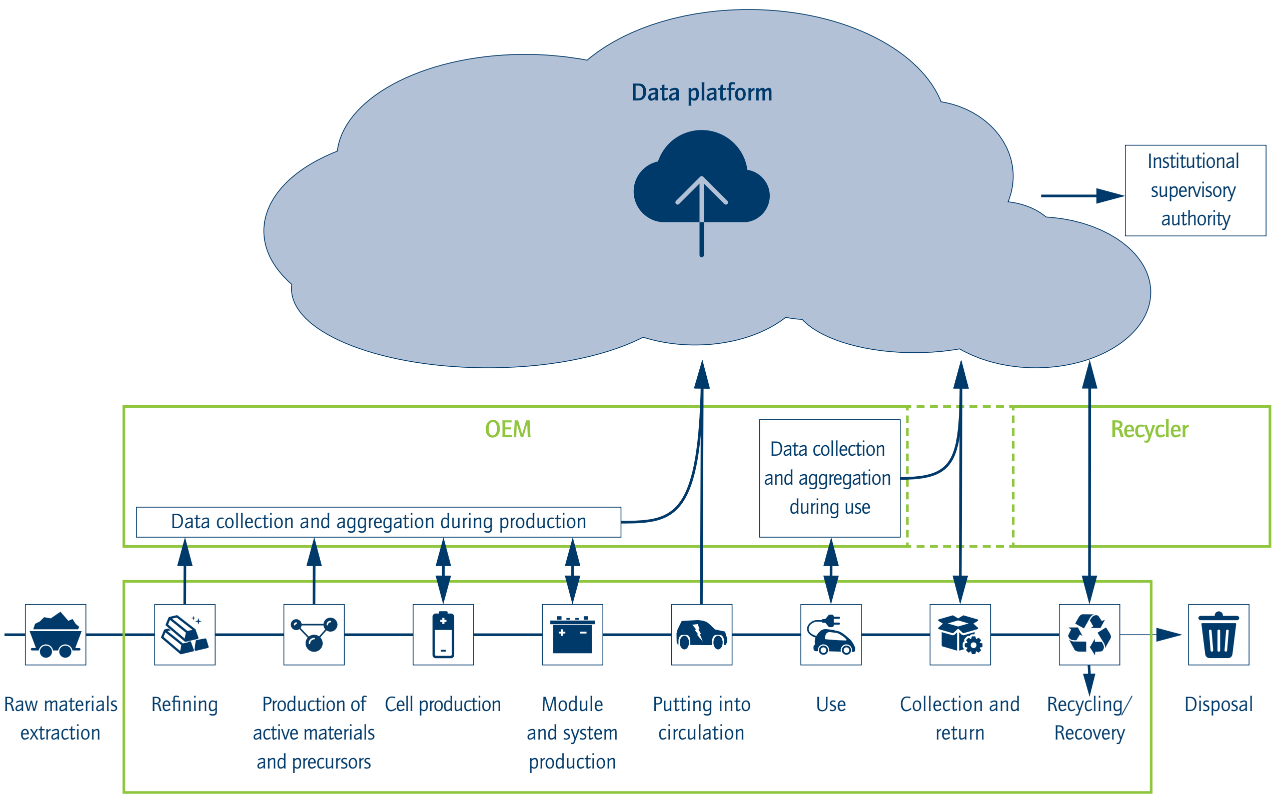

Figure 5: The core product of sub-working group 1 is recommendations concerning the information flows to promote the closed-loop recycling of traction batteries (Source: own representation, based on the representation of the World Economic Forum 2019)

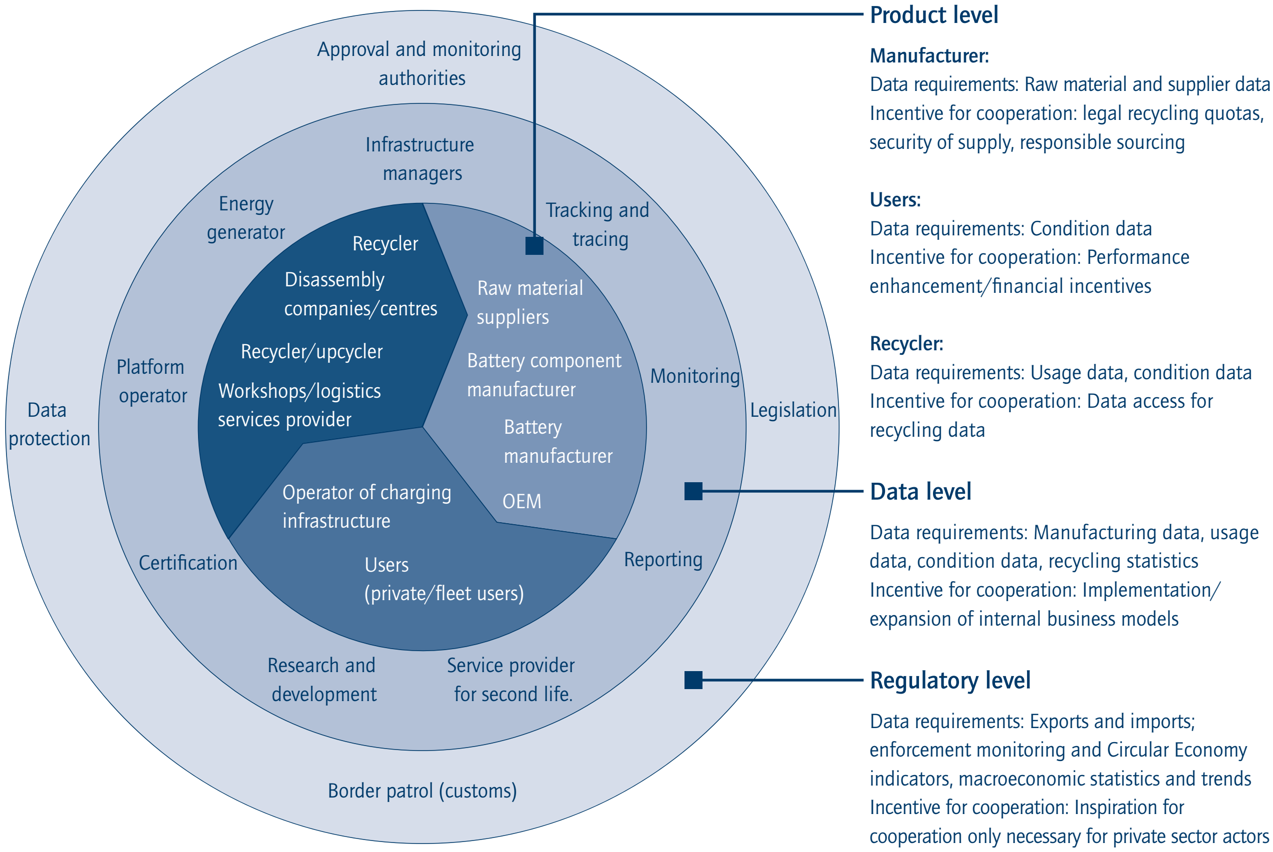

Figure 6: Actors, data needs, and incentives for cooperation for a pilot implementation (Source: own representation)

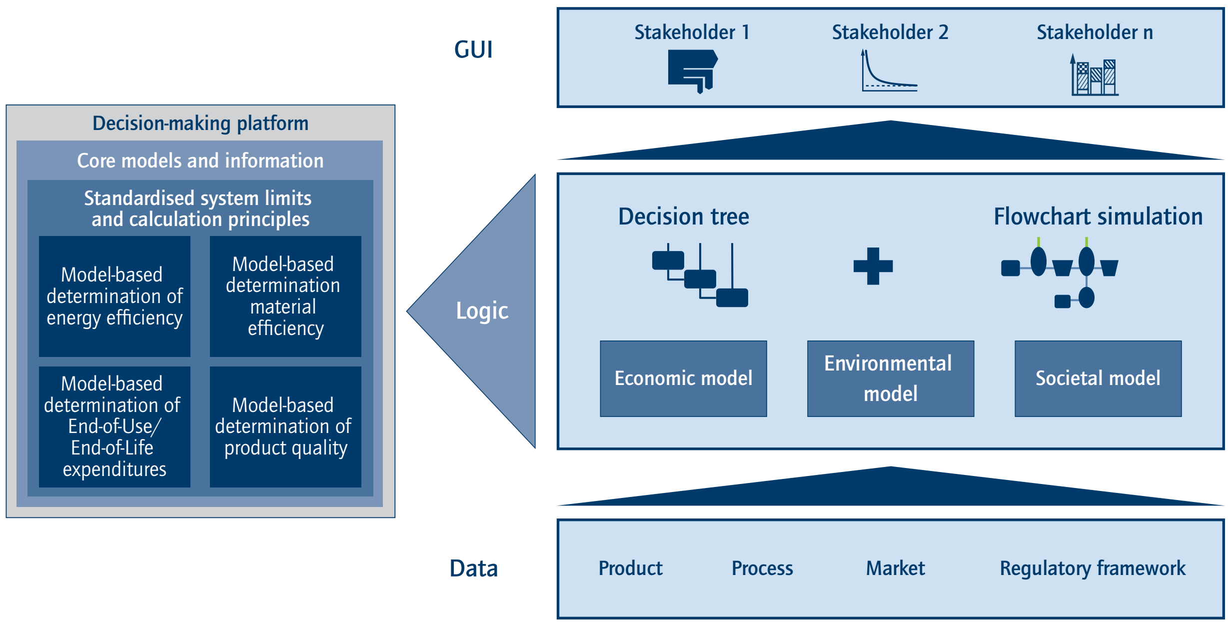

Figure 7: Model structure of the decision-making platform (Source: own representation)

1. Prolong the service life of traction batteries. How can the economic and environmental potential of second-life applications of traction batteries be realised, and to what extent is this desirable in its entirety (including longer dwell time of the materials in the cycle)?

2. **Close loops.** How are incentive and sanction mechanisms as well as value networks to be designed in concrete terms in order to ensure the optimal recirculation and high-quality recycling of traction batteries?

3. **Maximise systemic productivity.** How can the potential of traction batteries be used to optimise the electricity networks (sector coupling, vehicle-to-x – V2X)? What is the role of citizens and consumers?

In the context of the transformation towards a Circular Economy for traction batteries, these challenges must also be addressed.

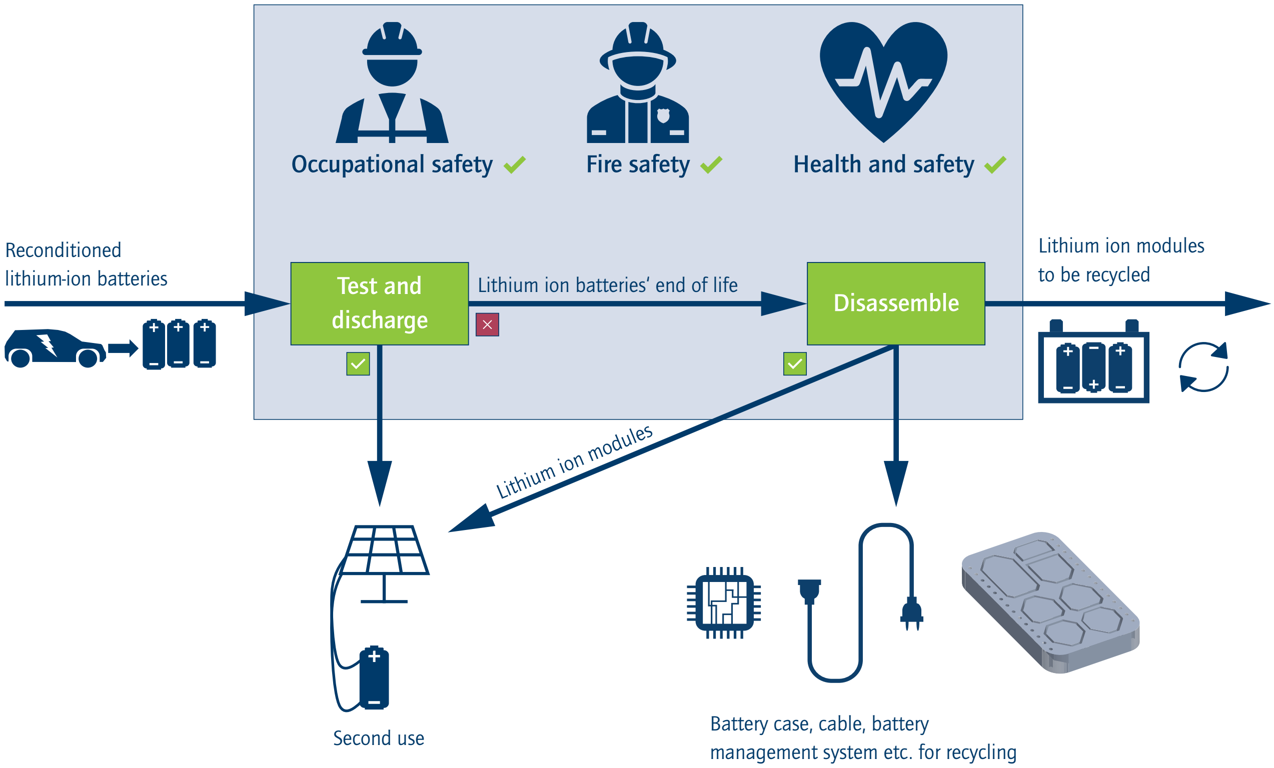

Figure 8: Concept of a dismantling facility for traction batteries (Source: own representation)

Next steps

With this report, the members of the Traction Batteries Working Group of the *Circular Economy Initiative Deutschland* contribute to the realisation of a Circular Economy for traction batteries. Like the sector as a whole, the Circular Economy is still in its infancy and continues to require strong interdisciplinary and collaborative exchange. Despite all the progress made in waste management in Germany, we are still a long way from a real Circular Economy in the sense of the vision described, and incremental improvements alone will not bring us any closer. A fundamental revolution in the design, use, and recycling of batteries coupled with regulatory system and business models that facilitate a systemic shift towards a physical Circular Economy is essential. The mandate goes to all involved actors in politics, business and science to immediately start developing and implementing of the options for action outlined here.

Aim and vision of the Circular Economy for traction batteries

Traction batteries represent a great opportunity for decarbonisation. However, they must be managed in terms of a smart Circular Economy. By 2030, traction batteries must be:

- designed for recycling management
- used in a highly productive fashion
- used as long as possible
- collected in their entirety
- ultimately recycled in high quality.

They can be a central element of a largely circular and thus resource-productive, decarbonised economy with minimum system losses and maximum raw material productivity. The recommendations presented here, including a roadmap, outline a path towards this vision. In order to make this a reality, decision-makers from politics, business, and science must implement measures in the short, medium, and long term.

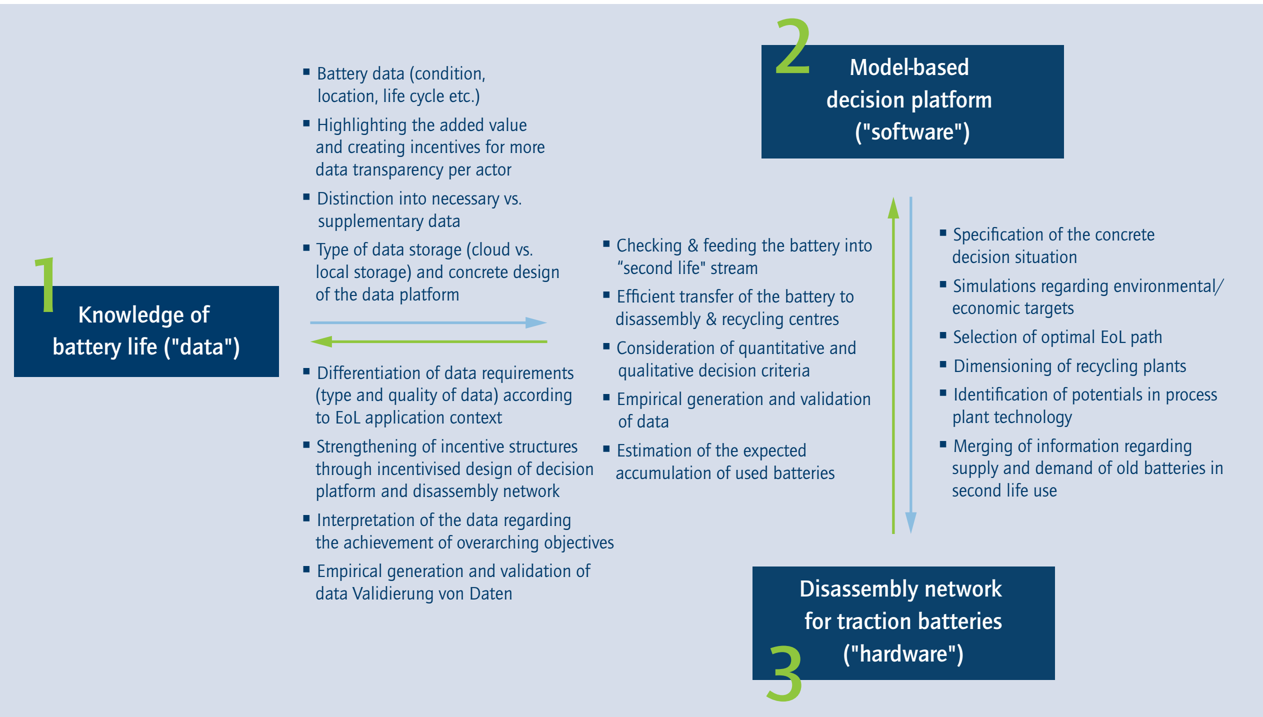

Figure 9: Interactions and synergies between the pilot topics (Source: own representation)

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1 Introduction

Timely decarbonisation of the transport sector is essential for **achieving the Paris climate targets**. In addition to a general reduction in the volume of traffic and an increase in multi-modal mobility offers, the rapid **scaling of the number of battery electric vehicles** (BEV)[16] **for individual transport** is of central importance. Even under today's conditions, after only 50,000[17, 18] – 80,000[19] kilometres driven, they have a better carbon footprint than vehicles with classic combustion engines. Recent studies even show that this can be the case for battery electric vehicles (BEV) with the latest battery generations under current conditions from as little as 30,000 km[20] and that these advantages are robust over a wide range of vehicle types and applications.[21, 22] In addition to the increased use of renewable energies in the production and use of vehicles, Circular Economy measures can contribute to further reducing the carbon footprint of battery production, including materials. In accordance with the scenarios of the National Mobility Platform, Germany's goal is to have approx. seven to ten million electric vehicles in Germany by 2030.[23, 24] Battery electric vehicles will probably make up the vast majority of the car population in the long term.[25, 26] It is therefore necessary to accelerate their market breakthrough and to make them socially acceptable and environmentally friendly.

Circular Economy[27] measures have the potential not only to further improve the environmental performance of battery electric vehicles but also to accelerate their market ramp-up through material supply and net cost reduction over the life cycle. They can also contribute to a more resilient economy and support resource decoupling[28] by making greater use of sources of secondary raw materials in their own country.[29] There is a need for a systemic, comprehensive approach that takes the entire life cycle into account – from designing the battery in a way that makes it easy to maintain and recycle to ensuring that the battery can be used as productively and for as long as possible to an effective recovery[30] and recycling infrastructure. Only in this way can a largely circular and thus resource-productive, decarbonised economy with minimised system losses and maximised raw material productivity be achieved in the long term.

Of particular importance in this context is the closing of the battery material cycle **(recycling)**.[31] Lifetime extension, for example by **repair,**[32] **refurbishment**,[33] or **remanufacturing**[34] can also lead to the continued use of batteries. Here, other stationary applications (second life, **SL**) can also make important contributions before the actual recycling. Circular Economy measures also exist during the use phase. These can increase the productivity of products and materials – especially through multiple use. These include in particular **smart charging (V1G/V2G/V2X)**[35] and **car- and ride-sharing**. These measures are intended to improve resource productivity in the battery value chain and to utilise the potential of consistent closed-loop recycling along the life cycle of the lithium-ion traction battery with the involvement of all relevant actors.

If **digital technologies and data** are also used extensively, the Circular Economy can be taken to a new level. By providing data relevant to business models across the life cycle of batteries (especially static data such as origin and environmental footprint, dynamic data such as remaining capacity, or even location data upon transfer of ownership), it is possible to optimise business and societal benefits at the same time – provided that data protection and confidentiality issues are resolved in the sense of a holistic Circular Economy. For the first time, digital technologies are enabling real end-to-end transparency on value losses and potentials of the new mobility and resource paradigm, which also includes ACES (autonomous, connected, electric, shared) mobility.[36] Last but not least, digital technologies and data increasingly enable automated circular measures (e.g. end-of-life tracking, (partial) dismantling, remanufacturing, and recycling) and thus more cost-effective, higher quality product and material (re)use.

16 | With regard to the current state of the art in electric vehicles, the term "electric vehicles" refers to battery electric vehicles (BEV), fuel cell electric vehicles (FCEV), range extended electric vehicles (REEV), plug-in hybrid electric vehicles (PHEV), and vehicles that recuperate deceleration energy and use it for support (Hybrid Electric Vehicles - HEV).
17 | See Regett et al. 2019.
18 | See Regett 2019.
19 | See Agora Verkehrswende 2019.
20 | See Hoekstra/Steinbuch.
21 | See Hill et al. 2020.
22 | See Transport & Environment 2020.
23 | See Nationale Plattform Zukunft der Mobilität 2020.
24 | Including hybrid vehicles and pure battery electric vehicles.
25 | See International Energy Agency 2019.
26 | Fuel cell vehicles will also contain lithium-ion batteries to ensure the driving dynamics and long service life of the fuel cell.
27 | See glossary.
28 | See glossary.
29 | See International Resource Panel 2019.
30 | See glossary.
31 | See glossary.
32 | See glossary.
33 | See glossary.
34 | See glossary.
35 | See glossary.
36 | See glossary.

However, while taking into account the potentials and challenges of digital technologies and data, targeted contributions are still required from the actors involved (in politics, business, science, and civil society) to create an appropriate **circular ecosystem** for traction batteries.

As underlined by the German Advisory Council on the Environment (Sachverständigenrat für Umweltfragen), there is still a long way to go from the "cycle-oriented waste management" currently practised in Germany to an actual Circular Economy.[37]

The open questions for traction batteries include, in particular:

1. Prolong the service life of traction batteries
    a. How can the implementation of design for circularity[38] in product and system design be accelerated?
    b. How can the conditions for environmentally and economically sensible and technically feasible second life applications be systematically fulfilled and ensured?
    c. How can the life cycle data of battery systems be made accessible to the industry from perspective of data protection and privacy?

2. Close loops
    a. Which innovative incentive systems can further improve the return of traction batteries to high-quality recycling structures?
    b. How can recycling quotas[39] and recyclate purity[40] be maximised?
    c. How can Circular Economy overcome the borders of a "nation state"?
    d. How can transnational, even global value networks be designed for the Circular Economy of traction batteries?

3. Maximise systemic productivity
    a. How can the potential of traction batteries be used to optimise the electricity networks (sector coupling, vehicle-to-x (V2X))?
    b. What (active or controlling) role can users play?
    c. How can the negative effect of geopolitical tensions on sustainable development be reduced?
    d. How do vehicle-to-x (V2X) and other multiple-use concepts such as car- and ride-sharing[41] interact – for example, in terms of battery ageing, user comfort, and downtime?

Discussing these and other questions and deriving corresponding recommendations for action was the goal of the Traction Batteries Work Group of the Circular Economy Initiative Deutschland (CEID)**.** Between October 2019 and May 2020, the Traction Batteries Working Group, which consists of leading economic actors in the battery value-added network and academic institutions in Germany, developed the basis for implementing the Circular Economy for traction batteries in Germany. This report contains the results of the working group.

The choice of the topic of traction batteries for the *Circular Economy Initiative Deutschland* was obvious for several reasons:

- There is a need for a systemic, comprehensive approach that takes the entire life cycle into account – from designing the battery in a way that makes it easy to maintain and recycle to ensuring that the battery can be used as productively and for as long as possible to an effective recovery and recycling infrastructure.
- Because of the great importance of the automotive sector for Germany as a business location and the central role of the traction battery in the incipient sectoral transformation to electromobility, the topic is of high economic relevance. The (ideally cheaper and more reliable) provision of important battery materials and substances – from essential battery metals to multi-material functional materials and complex material composites (see **glossary** for a detailed explanation) – can significantly improve the security of supply for key raw materials.
- At the same time, the sustainable design of this transformation by minimising the environmental footprint of the battery in production and over the life cycle is necessary to adequately utilise the decarbonisation potential of electric mobility. Circular Economy measures are essential for this because they increase resource productivity and have the potential to significantly reduce the use of primary raw materials.
- Finally, the traction battery can be a good reference example with a signal effect for other sectors. This can also be used to illustrate the transformation towards a Circular Economy. As explained in the following chapter, the Circular Economy is of the highest relevance for the electromobility sector. In addition to the further decarbonisation of traction current for the broad use of electromobility, closed-loop recycling is fundamental to further improving the eco-balance of electromobility and reducing dependence on important primary materials.

37 | See Sachverständigenrat für Umweltfragen 2020.
38 | See glossary.
39 | See glossary.
40 | See glossary.
41 | See glossary.

In-depth study I: Covid-19 and Circular Economy for traction batteries

By September 2020, the Covid 19 pandemic had claimed over 800,000 lives worldwide. The effects of the virus have been and continue to be severe: Apart from health aspects (the care of the sick, the measures needed to combat the spread of the virus, and the development of medicine and vaccines) and restrictions in public and social life, the pandemic led to probably the biggest recession of the last century. In response, trillion-dollar economic stimulus packages have been launched worldwide, including by Germany and the European Union.[42]

Commissioner Frans Timmermans stresses that the response to the Covid 19 crisis must be an integral part of the European Green Deal.[43] Appropriate investment programmes **should be geared to the transformation towards a sustainable economy** – for example in Battery Electric Vehicles (BEV), renewable energies, a climate-friendly infrastructure[44] – and a Circular Economy. Because of the essential contribution of resource use to climate change and the threat to planetary boundaries, it is essential to decouple prosperity from resource use. The Circular Economy is necessary for this and therefore also without alternative.[45] Decisions taken now will strongly influence the path of greenhouse gas emissions and resource use for the next decade.

Support packages must therefore be made compatible with the ambitious transformation path towards a climate-friendly Circular Economy.

This report from the Traction Batteries Working Group shows that **the Circular Economy provides clear long-term macroeconomic and specific benefits for traction batteries,** by increasing productivity, resilience, import independence, and employment security. For companies, similar benefits can be achieved through measures such as cost reductions, new business models, and better supply chain risk management. However, in order **to utilise these potentials, considerable targeted intervention is still required.**

The Covid 19 crisis also illustrates the target picture and transformation path proposed here: Serious changes in our way of life are possible, and selective measures that appear unusual may be appropriate. This would allow the testing and scaling up of new business models and value chain structures that would otherwise be legally impossible, too risky (for reasons of economic efficiency or antitrust concerns), or unprofitable. **Experiences from the response to Covid-19 should therefore be assessed in terms of their transfer to the transformation to a Circular Economy.**

The results of the traction batteries working group can also – or especially – in times of the Covid 19 crisis serve to enable first steps towards the transformation towards a climate-friendly, resource-decoupled Circular Economy for traction batteries.

1.1 Focus on traction batteries and embedding in the *Circular Economy Initiative Deutschland*

The results of the Traction Batteries Working Group are structured as follows in this report:

1. First, a common definition basis for circular battery value chain was created – for the **glossary** and the thematic **in-depth studies**, the work of existing initiatives was also taken into account and built upon.
2. Based on an **assessment of potentials and challenges** (see **Chapter 2**), a common **vision for 2030** is described, and possible conflicting objectives along the value chain are identified (see **Chapter 3**).
3. This is followed by the identification and analysis of concrete **pilot topics** that can make a significant contribution to achieving the vision (see **Chapter 4**).
4. This report is rounded off by the formulation of **recommendations for action** for politics, industry, and the scientific community (see **Chapter 5**) and the incorporation of these in a **roadmap** for the coming years (see **Chapter 6**).

The Traction Batteries Work Group has developed the content of three pilot topics building on each other with different focal points. It has also developed central challenges, approaches to solutions, and possible implementation schedules for each.

42 | See Nienaber/Wacket 2020.
43 | See Europäisches Parlament 2020.
44 | See Energy Transitions Commission 2020.
45 | See International Resource Panel 2020.

Pilot topic 1 "Understanding the service life of the battery" (see Pilot profile I, Annex I) addresses the requirements for setting up a common data infrastructure along the entire battery life cycle. This is intended to ensure the efficient collection, handling, reprocessing,[46] and recycling of batteries in downstream recycling and reuse steps (see chapter 4.1).

Pilot topic 2 "Model-based decision-making platform" (see Pilot profile II, Annex I) aims to develop requirements for data-based modelling that will enable economic targets to be quantified and provide quantitative support for operational decisions on the optimal use of batteries at the end of their service life (see Section 4.2).

Pilot topic 3 "Dismantling network for traction batteries" (see Pilot profile III, Annex I) deals with questions concerning the establishment of an industrial infrastructure that enables reverse logistics and dismantling of spentbatteries across national borders (see Chapter 4.3).

These pilot topics were identified by the members of the working group as central challenges – and thus, when addressed, potential points of leverage – for the successful circular management of traction batteries.

The results of the Traction Batteries Working Group are an integral part of the work of the *Circular Economy Initiative Deutschland* and are incorporated into the final report and the Circular Economy Roadmap developed therein.

1.2 Focus of the working group

In order to be able to look at the topic of traction batteries along its entire value chain, the traction batteries working group includes actors from business and science as well as topic-specific platforms and networks with different skills and expertise. The working group combines the specific views of several vehicle manufacturers, material and component manufacturers, recycling companies, and system service providers. On the research side, scientists from various disciplines complement the working group with their specialist expertise.

With the combined skills of the participants, the majority of the battery value chain can be covered: from the refining of the extracted raw materials to the manufacture and production of active materials, battery cells and systems to the application phase to the collection, return, and recycling of batteries (see Figure 10). Through the different expertise of the actors, new constellations for cooperation can be identified, and potential circular business models can be developed.

It does not consider the mining of raw materials or the disposal and landfill of residual materials. Nor does it consider the embedding of traction batteries in energy systems, for example via smart charging (V1G) and vehicle-to-grid (V2G) or vehicle-to-x (V2X). The participants in the working group expressly advocate exploring the potential of the latter because their potential for increasing systemic productivity makes them central elements of a Circular Economy.[47, 48] However, the working group itself concentrates on the product traction battery and the closed-loop recycling of this in the narrower sense.

A particular focus of the Traction Batteries Working Group is on digital solutions and data (including their processing) in order to improve incentives and information availability for the Circular Economy. One reason for this is the value of improved information on the localisation and efficient handling of batteries (e.g. transport, disassembly, reprocessing, and recycling). On the other hand, only sufficiently available information and data enable the creation of usage scenarios and business models in order to turn theoretically possible measures into reality.

The formulation of such measures is therefore the content of the three selected pilot projects. A more detailed discussion of circular business models, metrics, and the role of digital technologies for the Circular Economy can be found in the "Business Models" report of another working group of the *Circular Economy Initiative Deutschland*.[49]

46 | See glossary.
47 | See elementenergy 2019.
48 | See World Economic Forum 2019.
49 | The report of the Business Models working group will be published in autumn 2020.

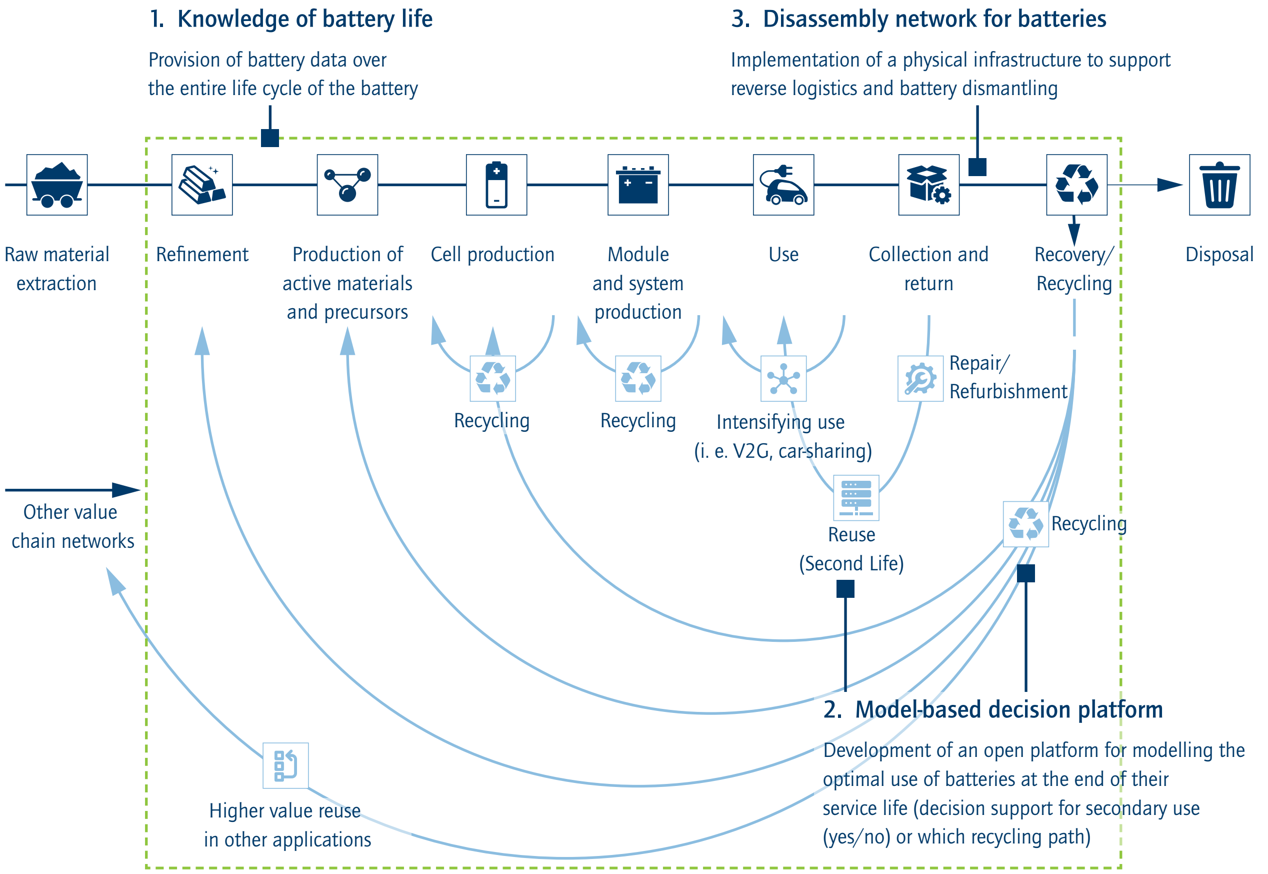


Figure 10: Illustration of the Circular Economy for traction batteries and scope of the Traction Batteries Work Group. Items 1 to 3 locate the pilot topics along the value chain (Source: own representation, based on the representation of the World Economic Forum 2019)

1.3 Other initiatives in comparison and added value of the *Circular Economy Initiative Deutschland*

Other initiatives also deal with Circular Economy in batteries. These include, in particular the umbrella concept "Battery Research Factory" of the German Federal Ministry of Education and Research (BMBF) with the cross-sectional initiative "Battery Life Cycle". This initiative is supported by the two BMBF competence clusters "Recycling/Green Battery" and "Battery Usage Concepts" (issues relating to ageing, service life, and second life). Other initiatives include the BMBF competence cluster "Battery Cell Production" (ProZell), the European Technology and Innovation Platform (ETIP) "BatteRIes Europe", the European Battery Alliance (EBA), and the Global Battery Alliance (GBA). The ReziProK projects of the BMBF are also worth mentioning because they work towards the goal of a resource-efficient recycling management in the automotive sector.[50]

The work of the *Circular Economy Initiative Deutschland* is compatible with the work of the aforementioned initiatives and addresses remaining gaps. The added value of the Traction Batteries Working Group within the *Circular Economy Initiative Deutschland* results in particular from

1. the creation of an open multi-stakeholder dialogue between business, politics, science, and civil society
2. the joint formulation of macro-perspectives, including perspectives on research and development, investment needs, market ramp-ups, and systemic information needs for politics and business

50 | See Bundesministerium für Bildung und Forschung 2020.

3. the identification of incentive/benefit combinations as well as possible obstacles and conflicting goals between relevant actors that can generate options for action
4. the identification of systemic interactions between the identified pilot topics and their contribution to the transformation to a resource-productive recycling management and exportable, future-oriented mobility carriers.

GLOBAL BATTERY ALLIANCE

- Global industrial initiative
- Goal: sustainably scaled battery industry
- Focuses: Principles of ethical material provision, battery passport, vehicle to grid

BATTERIES EUROPE

- EU platforms
- Focus: Support for the European battery industry
- Circular economy = recycling, in particular regulatory issues (Review of Battery Directive), securing of raw materials in the EU

Bundesministerium für Bildung und Forschung

Umbrella concept for the battery research factory:

- ProZell competence cluster for battery production
- Recycling/green battery competence cluster
- Focus on research support, technology solutions
- End-of-life considered

Circular Economy Initiative Deutschland

- Focus circular economy in Germany
- Guidelines for pilot projects on the Solution of concrete challenges
- Embedding in recommendations for national Circular Economy roadmap

Figure 11: Selective presentation of individual relevant initiatives for the Circular Economy for traction batteries (Source: own representation)

The work of the Traction Batteries Working Group is rounded off by the formulation of recommendations for action to establish and accelerate the Circular Economy for batteries – in Germany and beyond. The thrust of the working group also coincides with other expert bodies working on the Circular Economy (e.g. the Advisory Council on the Environment).[51]

51 | See Sachverständigenrat für Umweltfragen 2020.

2 Background of a Circular Economy for traction batteries in Germany

The transport sector currently accounts for around 24% of all CO_2 emissions worldwide[52] compared with 19% in Germany.[53] In contrast to the overall decline in emissions, transport emissions in Germany have actually risen by about 30% since 1990. This represents a major challenge for achieving the emission targets.[54, 55]

Especially in individual transport, solutions in the form of battery electric mobility are on the verge of a breakthrough as shown by the rapidly increasing market capitalisation of battery electric car suppliers as well as the ambitious electric strategies of established vehicle (parts) manufacturers. Because of the investments[56] of the automotive industry and the regulatory pressure in the form of the CO_2 fleet targets of the EU Commission of 95 grams of CO_2 per kilometre from 2020 and further reductions of 15% by 2025 and 37.5% by 2030 compared with 2021,[57] an exponential growth in the sales of electric vehicles is expected for the coming decade. In Germany alone, it is expected that in 2030, some 7 to 10 million electric vehicles will be registered. Of these, between 6 and 8 million will be battery-powered vehicles (Battery Electric Vehicle, BEV), and an additional 2 to 4 million will be vehicles with a plug-in hybrid drive (Plug-in Hybrid Electric Vehicle, PHEV).[58, 59, 60] Worldwide, 30–50% of the 90 million cars sold annually could then be electrified.[61]

Significant potential is also attributed to the fuel cell, especially in heavy-duty and air traffic.[62] However, the commercialisation of these has not yet been achieved. In addition, fuel cells for passenger cars are not expected to account for more than 5–10% of the electrified market in the long term.[63, 64] Finally, the application of fuel cells for passenger cars must be viewed critically from a climate perspective. This is because the systemic efficiency is less than half that of battery electric vehicles.[65] **The focus of this working group is therefore on improving the recycling management for traction batteries.** However, many of the approaches and recommendations for action also apply in principle to fuel cell vehicles (FCEVs), not least because these will always contain a lithium-ion battery for intermediate storage of the electricity generated.

2.1 Relevance of the topic of traction batteries for the Circular Economy

Because of the expected rapid growth in the market shares of battery-powered and plug-in hybrid vehicles, the annual production of lithium-ion (traction) batteries (LIB) is expected to increase considerably in the coming decade. The Global Battery Alliance estimates that demand could increase by a factor of 14 to 19 compared with 2018.[66] This would multiply the annual demand for key battery materials – especially for cobalt (by a factor of 2 to 3.6),[67] lithium (by a factor of 6.4), and nickel (by a factor of 24 for high-purity "Class 1 Battery Grade" material).[68]

On one hand, this market expansion worldwide promises great potential for new economic value creation and thereby increased prosperity. This could thus help to achieve the UN sustainability goals – not least in the raw material producing and manufacturing countries involved. On the other hand, the socio-economic challenges that can arise from this (e.g. extreme environmental pollution, occupational safety challenges, and human rights violations) must be minimised along the entire supply chain (from the extraction of raw materials to recycling) from the onset.[69]

It is therefore necessary to maximise the productivity of the materials used during the service life of the batteries and to guarantee safe recycling at the end of the service life. In this way, a "decoupling" of value creation and resource use, including associated environmental impacts, could be achieved as outlined by the United Nations International Resource Panel (UN IRP). Because resource use is responsible for 50% of all CO_2 emissions, 90% of water consumption and damage to biodiversity, and 30% of the health problems associated with air pollution worldwide, this

52 | See International Energy Agency 2020.
53 | See Umweltbundesamt 2020b.
54 | See Umweltbundesamt 2020a.
55 | See Agora Verkehrswende 2017.
56 | See Rauwald 2019.
57 | See Europäische Union 2019.
58 | See Boston Consulting Group/Prognos 2019.
59 | See Agora Verkehrswende 2018.
60 | See Nationale Plattform Zukunft der Mobilität 2020.
61 | See Buchert et al. 2019.
62 | See Hall et al. 2018.
63 | See Buchert et al. 2019.
64 | See VDI/VDE 2019.
65 | See Agora Verkehrswende/Agora Energiewende 2018.
66 | See World Economic Forum 2019.
67 | See Buchert et al. 2019.
68 | See World Economic Forum 2019.
69 | See World Economic Forum 2020.

decoupling is essential to respecting planetary boundaries and thus to the foundations of human well-being.[70]

Electrification shifts the environmental footprint of vehicles (greenhouse gases as well as other aspects such as particulate matter and eutrophication) from the end-of-pipe phase to the production of the electricity and renewable energy sources used (cradle-to-gate). Material management in the decarbonisation of transport is therefore becoming a central issue. Accordingly, the European Union[71] and China,[72] among others, are examining how life cycle assessment should be taken into account in the assessment of vehicle greenhouse gases.

The Circular Economy has great potential to combine socio-economic and economic effects by increasing resource productivity, minimising systemic losses, and safely reusing materials at the end of the service life.

Circular Economy is not an end in itself but rather should support the achievement of improvements in other sustainability goals. By integrating the needs of different interest groups and generating value through resource conservation, a Circular Economy can simultaneously improve various dimensions of sustainability.[73]

Ultimately, in order to achieve the aforementioned goals, mobility must be rethought in an integrative way, and the role of different modes of transport must be critically assessed. Circular Economy offers an opportunity to do this: for example, by focusing on systemic productivity improvements, accelerating innovation cycles through higher product utilisation, and expanding knowledge- and labour-intensive work steps.

For this reason, close cooperation with other German initiatives was sought. These include, in particular, Working Group 4 "Securing of the mobility and production location, battery cell production, raw materials and recycling, education, and qualification" of the National Platform Future of Mobility (NPM).[74] This assesses the competitive situation of the German industry in the areas of production of lithium-ion batteries for mobile applications and battery recycling (among others) and analyses the value-added potential as well as investment and personnel requirements of new mobility technologies.

Consultations with relevant European and global actors – such as the European Commission, the European Battery Alliance, and the Global Battery Alliance – were also included in the analysis.

2.2 Potential of Circular Economy for traction batteries

The literature contains numerous references to the potential of a Circular Economy. They were also presented by the European Commission in the publication of the European Green Deal (EGD)[75]: Elements of the Circular Economy can be found in at least five of the 10 pillars of the European Green Deal. Circular Economy is to achieve 50% of CO_2 savings by 2050.[76] The explicit consideration of Circular Economy in the revision of the Battery Directive[77] shows the great importance of the Circular Economy perspective for the European economy in general and the automotive and battery sector in particular. A Circular Economy can also support the achievement of various United Nations Sustainable Development Goals (SDGs).[78]

Specifically for traction batteries, the Circular Economy entails various possible measures over the life cycle. Of central importance are, in particular, the prolongation of life through **repair and refurbishment,**[79] the **continued use**[80] – if necessary after reprocessing – in stationary applications **(second life, SL),** and **recycling**. Productivity-enhancing measures during the use phase also belong to the Circular Economy for batteries, namely shared or multiple use **(ride- and car-sharing)** and **smart grid integration (V1G/V2G/V2X)**.[81] According to estimates by the World Economic Forum, if these levers are consistently implemented,

70 | See International Resource Panel 2019.
71 | See Europäische Union 2019.
72 | See Marklines 2017.
73 | See Weber/Stuchtey 2019.
74 | See Nationale Plattform Zukunft der Mobilität 2020.
75 | See Europäische Kommission 2019b.
76 | See Simon 2019.
77 | See Europäische Kommission 2019a.
78 | See Weber/Stuchtey 2019.
79 | See glossary.
80 | See glossary.
81 | See glossary.

total reduction potentials of around 40% of the carbon footprint and 20% of the costs of traction batteries could be achieved by 2030 through productivity gains, cost savings, and the improved recovery of valuable materials.[82]

- **Repair and refurbishment of batteries** can prolong the service life of batteries – both in the case of a fault before the end of the planned service life (repair) and in the form of refurbishment afterwards and the reuse in the same or another vehicle as a used battery. By replacing individual modules or control elements, for example, the remaining battery power can be increased again if necessary. However, the system-wide effect of a repair is likely to be relatively limited in the medium term because only a small proportion of the batteries are likely to require unscheduled repair. The economic added value for the replacement of individual modules or cells in the course of refurbishment could also decrease in the long term because of the increasingly homogeneous ageing of the battery cells in a battery pack.[83]
- **Second life (SL):** The reuse of traction batteries after the end of their first useful "life" in other, less demanding applications, possibly after their reprocessing, could show significant potential. For example, vehicle batteries that have been taken out of service could theoretically provide a large part of the demand for stationary power storage or buffers for network services in the future – if warranty and safety issues can be clarified. For this purpose, traction batteries as a whole or in individual modules would be converted for use in the electricity grid. Reuse in other mobile applications (e.g. electric scooters) is also being considered.

In-depth study II: Second life batteries

The environmental added value of using traction batteries in a second life (SL) seems clear, at least in theory. The vast majority of the studies on this subject have concluded that second life has the potential to significantly reduce the environmental impact of batteries – although the range is wide: Depending on the general conditions of the traction batteries used in second life, the reduction can be between 15%[84] and 70%.[85]

However, for a second life, safe handling and recording at the end of the first life as well as recertification, reprocessing, and marketing would first have to be clearly regulated and ensured. Further research and empirical experience are also needed to reliably estimate the actual technical and business potential of second life as well as the prerequisites for this. After an average of 8 to 12 years in the vehicle, these batteries not only compete with new generations of specialised batteries for mobile and stationary applications but their remaining service life could also be limited, or the probability of sudden/unanticipated failure could be increased because of non-linear ageing.

Accordingly, opinions on the actual amount of spent batteries available for second life applications (economic and technic) vary from 3[86] to 12[87] gigawatt hours per year in 2030 in the European Union (see figure 12). At the same time, the need for battery storage in Europe – so that more renewable energy can be fed into the grid – is estimated at four gigawatt hours per year from 2025.[88] Thus, second life could (subject to the conditions described above) make a significant contribution to meeting these needs in the medium term.[89] Because of the possible significant cost advantage of second life batteries compared with new batteries designed for stationary applications,[90, 91] there is a significant potential of second life

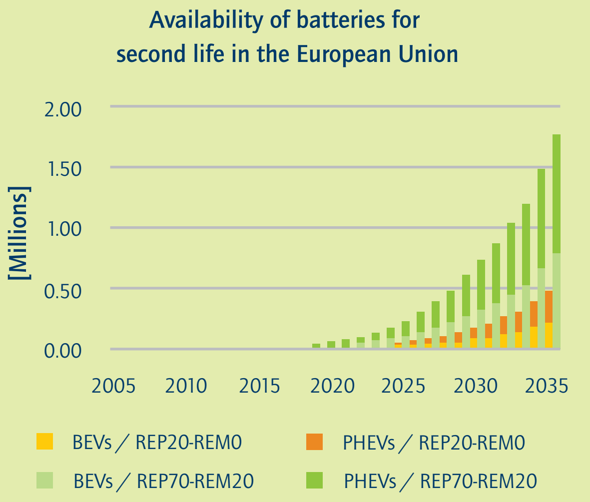
82 | See World Economic Forum 2019.
83 | See ebd.
84 | See Ahmadi et al. 2014.
85 | See Richa et al. 2017a.
86 | See Bobba et al. 2019.
87 | Note: Even for the lower values of 3 gigawatt hours, the study referenced assumes a second-life application of 20% of the spent batteries. However, this is viewed with scepticism by some actors from industry. | See Bobba et al. 2019.
88 | See Büscher et al. 2017.
89 | Note: The resulting delay in the availability of the batteries used in this way for recycling would be small – even in higher scenarios. Because of the constantly growing market, recycling accounted for only 1.5% of the global demand for cobalt. Of course, all batteries should be recycled in the long term.
90 | See Gsell/Marscheider-Weidemann 2020.
91 | Note: The costs for SL storage facilities are currently between € 50 and € 150 per kilowatt-hour; prices for new storage facilities in the stationary area are between € 200 and € 400 per kilowatt-hour. Both price points are developing dynamically. The service life of SL storage batteries is estimated to be about 0.5–10% of the service life of new stationary batteries. cf Gsell/Marscheider-Weidemann 2020.

batteries for the stationary battery storage market – if suitable regulatory and market supporting conditions are created.[92] However, this potential can be utilised to a greater extent only if structures are set up to provide professional access to spent batteries after their first life and if the battery data required to transform spent batteries into a second life are available. Ownership of the batteries and customised business models will play a key role in this process.

However, overall, the potential second life applications represent only a small proportion of the aged traction batteries available: Compared with the demand mentioned above, the production capacity of lithium-ion batteries will be around 500 gigawatt hours per year as early as 2020.[93] Therefore, it is likely that fewer spent traction batteries will be demanded for use as stationary storage than could be available; this would reduce their overall potential.

In order to enable that more second life applications, suitable regulations, are absolutely necessary,[94] among others:

- The most complete possible collection of spent batteries and their transfer to professional structures suitable for use in SL must be ensured. Processes for the return, testing, and provision of second life applications could, for example, be made mandatory by EPR systems.
- Information relevant for the end-of-life (EoL) assessment of traction batteries (state of health – SoH, safety, and/or other information relevant for second life suitability) must be shared between battery or vehicle manufacturers and potential second life users. The "how" must be clearly regulated, incentivised, and mandated.
- The determination of the end-of-waste status of end-of-life batteries to be transferred to a second life needs to be clarified. For example, these batteries could be exempted from waste legislation if they are proven (certified) suitable for second life applications.
- The transfer of liability (EPR, damage and product liability) between primary producers and second-life sellers must be clarified in order to ensure an appropriate incentive. Especially for vehicle manufacturers who put traction batteries on the market in their first life, incentives to cooperate with possible second users[95] such as network operators must be created.
- The environmental savings achieved through proven second life use should be creditable to climate inventories of car manufacturers in order to provide such incentives.



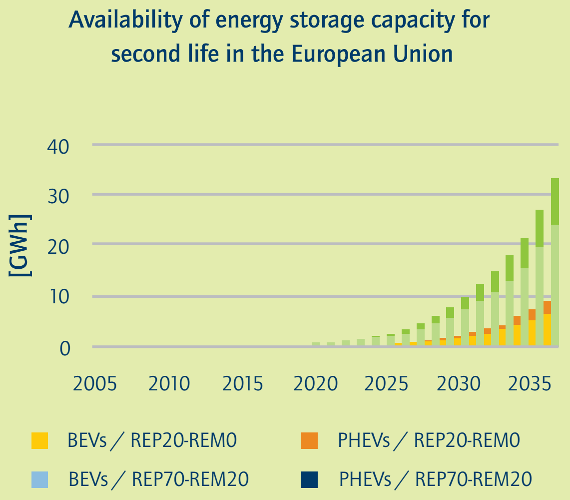


Figure 12: Estimated availability of second life batteries in stationary applications in the EU by 2030 in accordance with several scenario calculations (Source: Bobba et al.,2019)

92 | See Gsell/Marscheider-Weidemann 2020.
93 | See Thielmann et al. 2018.
94 | See Gsell/Marscheider-Weidemann 2020.
95 | See glossary.

- **Recycling** is one of the central measures of the Circular Economy: Ultimately, all batteries at the end of their service life – and of course also production rejects – should be subjected to high-quality recycling. With the appropriate scaling and process optimisation, recycling could provide about 10% of the demand for key battery materials and substances in 2030[96] (through market ramp-up, many more gigawatt hours of new battery cells will be produced, as spent battery cells become available for recycling). By 2050, this figure could rise to around 40% depending on the market ramp-up and the development of market shares of electromobility and cell chemistry.[97, 98] The use of recycled materials can contribute significantly to reducing the environmental footprint of batteries compared with the use of primary materials. This would depend on the material, battery type, and recycling method.[99]

  Battery recycling has been taking place for some time. However, the recycling rates are still too low (with the exception of lead-acid batteries such as starter batteries). The market ramp-up of traction batteries will also result in significantly higher quantities of batteries that, because of their size and the amount of energy they contain, will require different management than is possible today. As explained in more detail in In-depth study IV, the complete recycling of all important battery materials (e.g. lithium and graphite) is currently not economically viable. In addition, toxic components must be neutralised and safely handled in the course of material recycling. In order to enable actual closed-loop recycling in the physical sense, in addition to efforts to achieve high return, collection, and recovery rates,[100] high material qualities of the recyclates produced[101] are essential. Accordingly, consistent definitions of central terms should be determined, and success rates should be required for each important group of materials, taking into account high material quality (see Section 5.1 In-depth study: Battery recycling). Ultimately, the thermodynamic energy conservation (enthalpy and entropy (exergy)) of the entire system should be a central goal of the Circular Economy. It should therefore be striven for in the long term as a basis on which Circular Economy measures can be assessed.

Even though the following Circular Economy levers are not in the operational focus of the Traction Batteries Work Group, the **members of the working group expressly support them. This is because they may have significant potential for achieving a Circular Economy and thus a resource decoupling**.[102]

- **Ride- and car-sharing** of (electric) vehicles can increase the productivity of the traction batteries used by achieving higher vehicle utilisation (more passenger kilometres per kilowatt hour of capacity).[103, 104] Air quality and open space in cities could also be improved by decreasing traffic volume.[105] While car-sharing does not increase the utilisation of vehicles and batteries used per se, it does share other potential benefits of ride-sharing. These include higher vehicle mileage and improved incentives for life cycle management (fleet use in particular favours access to spent batteries at the end of the initial use phase). There is a potential for fleet-managed professional vehicles to be valued more on a total cost basis. This could promote the market ramp-up of battery electric vehicles. The faster wear and tear of individual vehicles could promote the speed of innovation. Finally, this could lead to an intensification of design for circularity, including more reuse and recycling. The globally estimated potential of ride- and car-sharing varies greatly between markets and depends on assumptions regarding the regulatory system and technical development (especially autonomous driving): The World Economic Forum estimates that by 2030, 16% of all vehicles worldwide will be managed in shared mobility services.[106] Others expect that by then in some markets 95% of all kilometres driven will be "shared".[107] In any case, the potential of higher

96 | See Buchert et al. 2019.
97 | See World Economic Forum 2019.
98 | See Öko-Institut 2017.
99 | See ebd.
100 | See glossary.
101 | See glossary.
102 | It should be noted that "sharing concepts", also known as Product-Service-Systems (PSS), do not automatically lead to environmentally optimal results. Rather, this must be considered as a goal in the design of the business model from the very beginning (see Hüer et al. 2018).
103 | Trade-offs between ride- and car-sharing and Vehicle-to-X (V2X) may include more frequent use of fast chargers in permanent fleet operation (which may reduce battery life) as well as less downtime and thus availability for network services.
104 | See Hüer et al. 2018.
105 | See Arbib/Seba 2017.
106 | See World Economic Forum 2019.
107 | See Arbib/Seba 2017.

car occupancy rates for better transport sector performance is generally recognised.[108, 109]

- **Smart charging, vehicle-to-grid, and vehicle-to-x (V1G/V2G/V2X)** are potentially the biggest levers for increasing productivity through additional revenue generation via various network services (e.g. balancing power, frequency regulation), higher product utilisation (multiple use), and cost savings in network infrastructure expansion. According to estimates by the Global Battery Alliance (GBA), up to 60% of global demand for stationary battery storage systems could be met in 2030 simply by using only a small proportion of the batteries of electric cars on the market for such applications.[110] The International Renewable Energy Agency (IRENA) estimates possible cost savings of up to 90% in the expansion of necessary grid infrastructure.[111] Their widespread implementation will require cross-sectoral measures by industry and politics between the energy and mobility sectors – for example, to harmonise energy markets and generate relevant industry standards between car manufacturers and energy market actors. On the other hand, user behaviour and interests (e.g. for example possible restrictions in comfort or flexibility) should be taken into account and addressed.

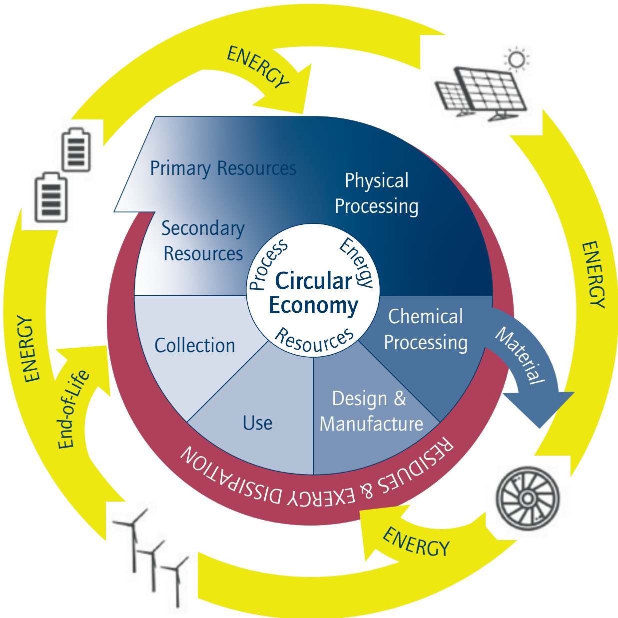


Figure 13: Conceptual representation of a Circular Economy for complex technical products based on thermodynamic assessment along the life cycle[112] (Source: Abadías Llamas et al. 2020)

The effectiveness of a Circular Economy can be analysed and described based on the systemic consideration of thermodynamic efficiency (enthalpy and entropy (exergy)), as shown in Figure 13.[112]

Further systemic changes could impact the relevance of Circular Economy levers. For example, the rapid (robotised) replacement of traction batteries (battery changing system, battery swapping) as already tested by actors such as Betterplace and Tesla[113] and further developed by Chinese car companies[114] and incentivised by the Chinese government[115] could extend the service life of the batteries and facilitate their maintenance or replacement. If it becomes widespread, this could lead to business models and value chains that are different from those currently in use (batteries handled separately from the vehicle) and increase the importance of maintenance and bidirectional charging (facilitated by the stationary management of the batteries in the exchange station). A major advantage for the Circular Economy in a battery replacement system is that the battery remains or must remain the property of the provider (B2B environment) and can be localised and managed in an integrated manner at any time. Questions of data availability, optimal maintenance, and access to batteries to use for second-life applications or high-quality recycling could thus be sufficiently addressed. However, because such systems are not (yet) widely used and it was not the subject of the Traction Batteries Working Group to assess the extent to which this concept is technically mature and feasible, it will not be discussed in any further detail.

In sum, the consistent implementation of the Circular Economy for traction batteries would bring a number of advantages, including:

- the reduction of (primary) resource consumption and the associated negative environmental impacts (in particular water consumption for lithium, carbon footprint of aluminium, and ecotoxicity for nickel and cobalt) and risks of human rights violations (in particular, for some forms of cobalt mining). As has been proven many times in studies,

108 | See ebd.
109 | See International Resource Panel 2020.
110 | See World Economic Forum 2019.
111 | See IRENA 2019.
112 | See Abadías Llamas et al. 2020.
113 | See Lambert 2017.
114 | See Lambert 2020.
115 | See Bloomberg 2020.

these advantages can be quite significant depending on the recycling process.[116, 117, 118]

- a contribution to the security of supply for the European battery industry – both against possible medium-term shortages in supply compared with material requirements and in relation to geopolitical dynamics such as temporary, politically mandated export restrictions.
- a reduction of battery costs over the life cycle of (up to about 20%) and thus an acceleration of the market ramp-up of electromobility and renewable energies (among other things, because the possibility of compensating for grid fluctuations through smart charging such as V1G/V2G/V2X).[119] One of the consequences of this is the need to systemically integrate the Circular Economy into (inter)national energy market policy and decarbonisation strategies.
- the potential for increased speed of innovation, among other things, through higher usage intensity in the fleet operation of vehicles and ride-sharing, inherent incentives for design for circularity, and faster achievement of critical mass for high-value circular business models. This emphasises the synergistic effects between "new mobility" – such as Mobility as a Service (MaaS) and the Circular Economy ecosystem – and consequently demands a systemic integration of the Circular Economy into (inter)national mobility strategies.
- the provision of additional battery capacities, also for stationary applications, and thereby an expansion of the market ramp-up as well as significant potentials for greenhouse gas reduction – not only in the mobility market but also in the energy market (approx. two gigatonnes CO_2 equivalents per year worldwide because of an increased share of renewable energies in the grid).[120] In this way, the Circular Economy supports a complete decarbonisation of the mobility and energy sectors – not only directly by reducing the greenhouse gas footprint in materials but also indirectly through systemic effects in other sectors.
- the potential of the Circular Economy to create jobs or relocate them to Germany should also not be neglected, because many activities in life extension, reprocessing, reuse, and recycling are often locally bound and relatively difficult to automate.[121] While the direct effect may be limited – for the European Union, for example, the Centre for European Policy Studies (CEPS) estimates the labour force required for collection, disassembly, and recycling at up to around 3,000 by 2030 and 15,000 by 2040[122] – additional effects are likely to create more jobs: For example, the availability of raw materials in Germany and the European domestic market will also favour the production of active materials in this country; this is currently located mainly in Asia and the US. In addition, the expansion of further business areas is expected – for example, around testing, (re)certification, remanufacturing, and network integration as well as systemically in the area of mobility and energy services.

For Germany as a business location, this means a multitude of advantages:

- greater depth of value added along the battery value chain in the domestic market followed by higher gross domestic product and greater resilience of German industry;
- improved human rights and environmental performance of battery electric vehicles followed by improved market and user acceptance (short term) and greater future security (long term);[123]
- less dependence on global material imports and prices followed by economic resilience;
- support of the structural change in the automotive and automotive supplier industry through future-oriented jobs and employment models as well as the generation of new market segments and business concepts; compare also the work of the NPM with which this report was coordinated;[124]
- Reclaiming an international leadership role in (climate and environmental) policy and technical innovations in future-relevant economic sectors

In order to realise the potential of a Circular Economy, comprehensive and concerted action by a large number of relevant stakeholders is required. After all, this is ultimately the creation of a new (and in parts radically different) economic system. This requires working towards a broadly supported vision of objectives, the progress of which can be measured. This was therefore one of the objectives of the Traction Batteries Working Group and is explained in the following chapter.

116 | See Buchert et al. 2011.
117 | See Mohr et al. 2020.
118 | See Ciez/Whitacre 2019.
119 | See World Economic Forum 2019.
120 | See ebd.
121 | See acatech 2020.
122 | See Drabik/Rizos 2018.
123 | See World Economic Forum 2019.
124 | See Nationale Plattform Zukunft der Mobilität 2020.

In-depth study III: Quantified material flow analysis of a Circular Economy for traction batteries

The SUN Institute Environment & Sustainability commissioned the Wuppertal Institute[125] to perform a material flow analysis on the Circular Economy (CE) for traction batteries. The Wuppertal Institute additionally quantifies the CE vision with regard to possible effects on material flows, energy consumption, CO_2 effects, and economic parameters in an initial assessment.[126] The calculations are based on database and literature evaluations (including the renowned life cycle database ecoinvent 3.6), which are always subject to certain uncertainties, especially with regard to future trends and technological developments. Because of this, they represent only the average of a broad spectrum of technologies.

1. **Recycling**: If it were possible to optimise the **recovery rates** for the key raw materials from batteries to 90% for nickel and cobalt and 85% for lithium (both in battery quality) and at the same time increase the recollection rate to 90%,

   i. assuming that no second life applications become possible, 8,100 tonnes of lithium, 27,800 tonnes of cobalt, and 25,700 tonnes of nickel could be recovered by 2030, and a total of 109,000 tonnes of lithium, 180,000 tonnes of cobalt, and 576,000 tonnes of nickel by 2050.
   ii. lithium for 1.3 million (2030) and 17.7 million (2050) additional electric vehicles could be made available through recycling.[127] The amount of lithium, cobalt, and nickel corresponds to an economic value of € 1.2 billion by 2030 and € 13.8 billion[128] by 2050 and would cover the demand for lithium for **battery electric vehicles** (BEV) by about 13% by 2030 and by about 39% by 2050 (because only then will end-of-life vehicles be increasingly decommissioned compared with the market growth of new vehicles).
   iii. through **recycling**, 329 petajoules could be saved by 2050 (taking into account the energy and resources needed for the recovery process). Under simplified assumption of the application of the current electricity mix in Germany, this would correspond to CO_2 emissions of about 36 million tonnes,[129] which is about 10% of the CO_2 emissions generated by the production of recycled car batteries.

2. Refurbishment: If it were possible to refurbish 25% of the spent vehicle batteries from 2030 onwards and to replace them in the original vehicles, this would result in savings of around € 5.3 billion and 282 petajoules in energy requirements (31.4 million tonnes of CO_2 equivalents).

3. The potentials of using used traction batteries in stationary applications – **second life (SL)** – are controversially debated. This is why different sensitivities were calculated (0%, 20%, and 50% second life rate). Based on a scenario with an optimistic second life rate of 50%, the cumulative energy demand (CED) from 2020 to 2050 could be 655 petajoules (73 million tonnes of CO_2 equivalents) – assuming full substitution of nickel-manganese-cobalt (NMC) batteries. This would correspond to approximately 1,300 billion kilometres driven with a light battery electric vehicle (BEV),[130] twice the mileage of all passenger cars in Germany in 2018.[131] However, this high rate has to be considered as an upper limit because much smaller quantities are likely. These will strongly depend on the regulatory market design, the business models applied (in particular the ownership and warranty obligations of the battery), and the efficiency of the re-marketing as stationary batteries (see in-depth study on second life batteries).

   i. In view of the ramp-up of electric mobility in Germany, more than half a million end-of-life **(EoL) traction batteries** can be expected annually from around 2030. If 50% of the batteries were put into a **second life**, this date and the associated potential for material recovery and the need for correspondingly increased recycling capacities would be delayed by about 4 years. At the same time, the batteries used in second life would continue to generate added value during this period, for example in the energy sector by providing network services.

125 | See Wuppertal Institute [forthcoming].
126 | For an explanation of the underlying assumptions and their basis, see Annex H.
127 | Second Life 0%, export quota 0%; need for a nickel-manganese-cobalt (NMC) 111 battery
128 | Calculated at current market values (April 2020).
129 | See Umweltbundesamt 2020a.
130 | See Fritz et al. 2016.
131 | See Kraftfahrt-Bundesamt 2019b.

ii. If 50% of the end-of-life (EoL) traction batteries produced were used in second life, this could lead to a **capacity of** around 58 gigawatt hours of **stationary power storage** by 2030. This would correspond to a saving of 69.6 petajoules in cumulative energy demand (CED) for the bypassed production of additional batteries. This could avoid 7.8 million tonnes of CO_2-equivalent greenhouse gases.

A more detailed description of the modelling is given in Annex H. The full study is in progress and will be published.[132]

132 | See Wuppertal Institute [forthcoming].

3 Vision for a Circular Economy for traction batteries

The members of the Traction Batteries Working Group developed a common vision for traction batteries for the year 2030. In order to achieve this vision, the recommendations for action derived in Chapter 5 and the roadmap described in Chapter 6 were drawn up.

Building on central basic assumptions formulated by the Traction Batteries Working Group (see Section 3.1) and the description of framework conditions for a long-term (2050) greenhouse gas-neutral and resource-productive economy (see Section 3.2), the vision itself is described in chapter 3.3. Possible exchange relationships (trade-offs) are explained in section 3.4.

3.1 Basic assumptions of this report

The following considerations underlie this report:

1. The electrification of individual transport will probably be covered by battery electric vehicles (BEV) by a large majority (see Chapter 1, Introduction). **The working group is therefore focusing on this segment of traction batteries**.
2. At the same time, the expansion of green hydrogen is to be advocated as a basic condition for the decarbonisation of (basic) industry, aviation, as well as parts of heavy-duty and long-distance transport.
3. A rapid market ramp-up of (battery) electric mobility requires the implementation of the Circular Economy through a robust ecosystem. This must provide an adequate and cost-effective charging infrastructure, an expansion of shared mobility services to better utilise the lifetime cost benefits of battery electric vehicles (thus enabling the continued use of suitable batteries at the end of their life), and sufficient capacity for efficient and high-quality material and material recovery.
4. The working group supports an ambitious expansion of renewable energies because the decarbonisation of the energy used for the production, transport, and recycling of batteries contributes significantly to their carbon footprint. A battery production with 100% renewable energies is already possible in many production steps and is explicitly supported by the working group.
5. Contrary to public perception, the carbon footprint of battery electric vehicles is already today usually lower than that of an equivalent vehicle with conventional drive (as explained in Chapter 1, Introduction). This advantage will improve significantly with the increasing share of renewable energies in the production and use of vehicles, optimised manufacturing processes, and improved Circular Economy measures.
6. In the design of Circular Economy measures that are in-line with planetary boundaries, the optimisation of environmental parameters must be considered a priori. These include greenhouse effects (CO_2) as well as factors such as biodiversity, freshwater resources, (human) toxicity, ozone pollution, and aerosol pollution, since these can all be negatively influenced by resource use. It is self-explanatory that compliance with occupational safety and human rights must be ensured under all circumstances along the entire supply chain.[133]
7. Ultimately, the thermodynamic energy conservation (enthalpy and entropy (exergy)) of the entire system should be the goal of the Circular Economy. It should therefore be the basis of assessment of a Circular Economy in the long term. The use of engineering process simulations based on empirical validation is recommended for the exact determination of these measured variables.[134] Based on process-specific data (securely and completely collected and stored across the value chain, for example through "material passports")[135, 136] simulations can provide a detailed digital representation of processes and the environmental effects of complete production networks – from raw material extraction, production of performance materials, and product design to the recycling and re-marketing of recycled materials.[137] This can create the physical link between processes and interest groups and thus be a key aspect in the assessment of battery (re)designs and compatibility with the flexible and available processing infrastructure of a successful Circular Economy.[138, 139]
8. The Circular Economy for traction batteries is inherently embedded in the international context, in particular that of the European Union. The conditions for the management of traction batteries should apply to all products placed on the German or European market. At the same time, German

133 | See Cerdas et al. 2018.
134 | See Reuter et al. 2015.
135 | See glossary.
136 | See Europäische Kommission 2020.
137 | See Bartie et al. 2020.
138 | See Reuter et al. 2015.
139 | See Bartie et al. 2020.

products will be used especially in other European and international countries. Wherever the end-of-life (EoL) takes place, the return to the cycle and, in the end, high-quality recycling must be guaranteed. End-of-life batteries or fractions thereof are also transported across borders to be processed in the most suitable facilities.

9. Today, international recycling markets and flows are not always transparent enough and do not always take into account the legal framework, human rights, and/or environmental requirements. The Circular Economy for traction batteries should therefore not least contribute to improving these aspects, for example by ensuring that batteries are managed throughout their life cycle by professional actors in accordance with best practice.
10. In order to achieve a Circular Economy, not least the appropriate training and cultural change are indispensable to support ambitious policies and enable the concrete implementation of measures.
11. The working group supports the principles for sustainable batteries of the Global Battery Alliance. These include the Circular Economy for batteries and cover:

    - the productive and safe use of batteries in order to achieve the Paris Climate Targets
    - the assurance transparency, energy efficiency, sector coupling, and use of renewable energies
    - the focus on the creation of good jobs worldwide
    - the unconditional respect of human rights orientation towards the UN sustainability targets.[140]

3.2 Framework condition of a greenhouse gas neutral Germany as part of a European Circular Economy by 2050

The long-term vision of the Traction Batteries Working Group is a largely circular and thus resource-productive, decarbonised economy with minimised system losses and maximised raw material productivity as envisaged in the Resource Efficiency Programme of the Federal Environment Ministry (BMU; ProgRess III).[141, 142] It should thus be possible to achieve a far-reaching absolute decoupling of prosperity from resource use (i.e. to reduce the absolute demand for resources as prosperity increases as called for by the UN International Resource Panel (IRP)).[143]

In doing so, the working group on traction batteries relies on development paths that are compatible with a two-degree Celsius climate scenario. This means, among other things, that in 2050, only electrified cars will be sold. Of these, about two thirds will be battery electric vehicles (BEV).[144]

In the long term this means

- a battery sector in which 100% renewable energy is used in production, use and recycling,
- that all batteries are also designed and constructed according to principles of circularity (design for circularity, including facilitating repair and disassembleability),
- where possible, the use of raw materials with high human and eco-toxicity and human rights and environmental footprints is reduced
- (systemic) material and energy efficiency in production, use, and recycling of traction batteries are maximised
- batteries in the use phase are managed for maximum productivity – including smart and, where appropriate, bi-directional charge management and high levels of fleet operation, especially for ride-sharing
- traction batteries can be tracked until they are reliably reused so that a collection rate of almost 100% can be achieved, thereby minimising system losses (minimal leakage)
- all batteries collected at the end-of-life (EoL) are fed into the environmentally and economically optimised path via further use (second life) for reuse (where sensible)
- environmentally friendly, efficient recycling processes ensure optimal, high-quality material recovery throughout the entire recycling process (see in-depth study on battery recycling)

To be successful, the Circular Economy requires a transformation of the economy so that products and resources are used in a

140 | See Global Battery Alliance 2020.
141 | See Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2019.
142 | The aim of the German Resource Efficiency Programme (ProGress) is a more sustainable extraction and use of resources. In order to achieve this, the German government is striving, among other things, to decouple economic growth from resource use as well as to reduce the associated environmental pollution. The third edition of the programme is currently available in draft form (ProgRess III). The innovations it contains include the consideration of “mobility” from the point of view of resource efficiency and the sustainable use of worn-out traction batteries.
143 | See Weber/Stuchtey 2019.
144 | See Buchert et al. 2019.

Area	from …	to …
Competition	Competition	"Coopetition": Collaborative business models
Understanding of value	Value defined by short-term monetary success	Long-term, holistic (economic - environmental – societal) creation of value
Incentives	Waste disposal by Extended Producer Responsibility	Life cycle management through producer ownership
Flow of information	Fragmented commodity markets	Platform considering transparent, eco-social principles
Use of resources	Optimisation for fast linear product throughput and thus material throughput	Holistic value maximisation through focus on productivity and value preservation
Basis of value creation	Mass production	Smart use of information

Figure 14: Circular Economy means an economic transformation in many areas (Source: own representation)

highly productive manner. This would form the basis for Germany to remain one of the most competitive business locations in the world in 2050 (see Figure 14).

3.3 Vision 2030 of a Circular Economy for traction batteries

In order to operationalise the transformation towards a decarbonised, Circular Economy, the participants of the Traction Batteries Work Group developed a common vision along the five dimensions of regulatory system, material flows, technical development, value networks, and internal implementation. These are to be harmonised with the resource productivity targets for 2030 defined in ProgRess III.[145] The vision does not claim to be complete. Instead, it aims to highlight selective aspects of a Circular Economy that are important to members in order to create a common understanding of a possible and desirable future and to facilitate coordinated action.

Objectives for the regulatory system

- Measures to achieve a high level of **transparency on the whereabouts, condition, and eco-performance of batteries** are implemented – for example, battery label, greenhouse gas footprint, battery production, cradle-to-gate, and/or mandatory digital provision of relevant information on the battery throughout its life cycle (from production to end-of-life management and reuse of raw materials and materials).
- **Data protection and security** are guaranteed. Data is collected only where it is useful (for example, no live tracking but only when ownership is transferred).
- **Uniform international standards regarding the end-of-life treatment and logistics** of traction batteries – including the clear formulation of key definitions (e.g. recycling, refurbishment, second life, and end-of-waste) – have helped to eliminate unfair competition as far as possible. As a result, legally compliant and economic business models have become established on the market.
- **Responsible sourcing,**[146] **high-value reuse and responsible recycling**[147] will be harmonised through the EU internal market and given **regulatory incentives**. In line with the rapidly growing market for traction batteries, this has led to a rapid

145 | See Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2019.
146 | See glossary.
147 | See glossary.

§ Regulatory framework

- Knowledge about the **whereabouts, condition, and eco-performance** of batteries while maintaining data protection and security
- **Uniform international standards** for EoL treatment and logistics
- EU-wide harmonised regulatory framework, including **incentives** for responsible sourcing, high value reuse, and responsible recycling
- **Level playing field** for participating actors through new edition of the EU Batteries Directive
- **Standardised method** for the determination and crediting of recyclates

Material flows

- Development of **tools** for tracking and eco-social decision making (e.g. **battery passports**, data spaces, LCA simulations)
- **Secure databases** with standardised interfaces and transparent protocols
- Clarity as to what extent **V2X and second life applications** of traction batteries are economically and environmentally reasonable
- **Collection and high-quality recycling (if suitable after Second Life) of all traction batteries** at the end of their service life
- **Post-consumer recyclates** represent a small (~10%) but growing part of the demand for key battery materials

Technological development

- **Design for circularity**/design for recycling and modularity are industry standard
- **Digital industry standardisation** and smart manufacturing (Industry 4.0, AI, IoT, Blockchain) flexibly support manufacturing and EoL management
- **Reliable provision of information through digital technologies** (e.g. Battery Passports, Digital Twins)
- **Increasing automation of maintenance and disassembly** resulting in cost savings and safety
- **Advanced recycling technologies** with high performance

Value networks

- **Decarbonisation of used materials** is a **strategic component of** the business of product manufacturers
- **Value creation increasingly collaborative** and across (several) life cycles of the battery
- **Management of batteries** across actors and the entire life cycle (cradle to cradle)
- **New roles** of existing actors and new market participants
- Proliferation of **digital platforms**
- **Strategic and operational integration** of the energy and transport sector in terms of sector coupling

In-house implementation

- **Efficient and safe handling** of the rapidly increasing quantities of EoL batteries **through effective disassembly networks (disassembly, assessment, transport)**
- **Application of new B2B/B2C business models** for circular product management
- Widespread use of **new economic indicator systems** (especially accounting)
- **Resource productivity** of the still expensive traction batteries is optimised by many actors (Ride-sharing and pooling, V2X)

Figure 15: Vision of the working group for a Circular Economy for traction batteries (Source: own representation)

increase in the market for recycled and possibly also reused second life batteries.

- The new edition of the **European Batteries Directive has created a level playing field** and incentives for eco-design (including consideration of the ecotoxicity of the substances used and their safe handling over the life cycle) for the actors involved. This is done, among other things, by clearly defining central terms, setting meaningful recycling targets, and naming product information relevant for the recovery of the most important functional materials and metals and for a transnationally standardised query (examples of relevant product information are battery type, environmental or greenhouse gas footprint, and state of health).
- A standardised procedure for determining and crediting recycled shares in the raw materials available on the market enables precise, realistic, and (for consumers) transparent **environmental assessments** of batteries. These evaluations are increasingly based on the simulation of exergy/entropy of the entire traction battery system[148] (see in-depth study battery recycling) so that the effects of measures on energy and material flows can be integrated equally.

Targets for material flows

- The whereabouts of batteries, their components, and materials at the end of their life can be traced by **tracking and tracing tools such as product or battery passports** along the entire life cycle as well as across national borders. This turns the vehicles into valuable "virtual mines". Material losses – especially of central battery metals and materials – from the system are thereby largely avoided.
- **Secure databases with standardised interfaces and transparent protocols** provide actors along the value chain with customised information while ensuring the protection of intellectual property and competitive advantages (see International Data Spaces). Private sector solutions complement those of the public sector.
- Relevant **research and development** on battery ageing, testing, and safe handling has led to clarity **on the extent to which** vehicle-to-x **(V2X) and second life applications of traction batteries make economic and environmental sense**. Accordingly, these applications improve the cost-effectiveness of battery storage and take a share of the market for otherwise new battery capacities.
- **All traction batteries are collected at the end of their first life** and, after possible refurbishment or, where appropriate, a second life application, are ultimately subjected to efficient and high-quality recycling. As a result, in 2030 **post-consumer recyclates** will represent a small (about 10%),[149, 150] but increasing share of the demand for important materials for lithium-ion batteries (significantly higher values will be achievable only after the market ramp-up for electric vehicles has flattened out). This significantly improves the carbon and environmental footprint of batteries.

Objectives for technical development

- **Design for circularity** has become the industry standard in many cases and allows the safe and efficient handling of batteries for circular business models throughout the battery life cycle. Greater modularity and both constructive (design for repair) and destructive (design for recycling) design principles are taken into account and support more automated measures.
- **Digital industry standardisation and smart manufacturing** (industry 4.0, artificial intelligence, internet of things, blockchain) help to make the repair, reuse, and recycling of battery (components) more efficient. Here, the manufacturers' ability to innovate and differentiate is ensured by maintaining flexibility in the manufacturing process and product design.
- The widespread use of advanced digital technologies such as tracking and tracing technologies **(material and product passports and Circular Economy data spaces)** and simulations (digital twins, system simulations, including exergy/entropy of the overall system of traction batteries) and their versatile integration into business (IT) systems enable reliable information to be provided on the whereabouts of the batteries and environmentally and economically optimised decisions to be made while guaranteeing data protection and security.
- This also enables the **increasing automation of maintenance and dismantling**, which results in the scaling and cost reduction of reuse and end-of-life activities. Nevertheless, the Circular Economy for traction batteries remains a job engine because a great deal of expertise and human intervention remains necessary even in almost fully automated processes. The automation of dangerous processes also increases safety for personnel and simultaneously reduces costs.
- Compared with 2020, recycling technologies are significantly more (energy) efficient, economical, safe, and effective (especially in terms of yield and purity) in the production of

148 | See Section 3.1 Basic assumptions Item 7.
149 | See Buchert et al. 2019.
150 | See Agora Verkehrswende 2017.

high-quality recyclates. Most important materials can thus be recovered in a high-quality and profitable manner.

Targets for value networks

- Because of the **high and still increasing share of renewable energies,** the focus has increasingly shifted to the **decarbonisation of battery materials.** Circular Economy provides answers to this question. Whereas decarbonisation of the material was previously the responsibility of upstream or downstream market participants, it is now part of the business of product manufacturers and vehicle (parts) manufacturers. This area of responsibility is covered partly by acquisitions, partly by the expansion of existing business models, and partly by cooperation. In this way, the "cooperation" that often arises in the context of the Circular Economy is filled with life – Round Stream[151] begins to exist.
- **Value creation is increasingly collaborative** and happens over (several) battery life cycles. This results in a horizontal networking of the value chain. Increasing integration increases the value of open cooperation and data sharing to enable mutual revenue and value generation. A new concept of "value" is beginning to establish itself.
- Batteries are **managed** across actors **throughout their entire life cycle (cradle-to-cradle).** This leads to completely new business models and constellations of actors.
- **New roles** for existing actors (no classic thinking in upstream/downstream) and completely new fields of activity with new market actors are developing.
- The **proliferation of digital platforms** for batteries and their materials has led to a high degree of transparency and market efficiency, thereby enabling a variety of new business models for new and old market participants.
- This is accompanied by a **strategic and operational integration of the energy and transport sector** in the sense of sector coupling. This supports sustainable technological and social trends (especially electromobility, energy turnaround, and Industry 4.0).

Targets for internal implementation

- **New actors** are emerging to serve the mass market of end-of-life batteries (e.g. specialists in logistics, reuse, and recycling).
- The establishment of effective **dismantling networks** (dismantling, assessment, transport) has led to the efficient and safe handling of the rapidly increasing quantities of end-of-life batteries. The **early management of the market ramp-up** of the dismantling facilities has resulted in an efficient combination of decentralised and centralised sites and systems.
- **New B2B/B2C business models for circular end-of-life management** are increasingly being used and improve the return, reuse, and recycling of batteries – for example with deposit models (B2C) (see in-depth study on deposit systems) and leasing models (B2B).
- New **business performance measurement systems (especially accounting)**, which represent new circular business models and their value flows on an eco-social and economic holistic basis at the organisational and product level, have found widespread application and are published and tracked according to their contribution to achieving (inter)national targets for resource productivity and efficiency.
- Various actors are helping to optimise the resource productivity of the still expensive traction batteries – for example through **ride-sharing and pooling** and the resulting high number of passenger-kilometres per vehicle (vehicles remain in company hands). Product-as-service business models increase material efficiency throughout the entire production cycle (B2B).

3.4 Environmental, social, and economic exchange relations (trade-offs)

The transformation towards a Circular Economy aims to harmonise competing and sometimes contradictory interests and criteria. This is particularly true:

- for the transformation from linear to circular value creation
- between different possible circular approaches
- and within individual approaches in which competing criteria need to be optimised (e.g. material yield and energy consumption).

Challenges will arise in particular during the market ramp-up to 2030. This is because the high investment requirements were unsteady and will face sub-critical returns from vehicle batteries. At the same time, state interventions (regulatory and/or financial) have not yet been optimised for the new value chains or networks, and industry standards are lacking. The fair distribution of efficiency gains through systemic Circular Economy optimisation among the actors also still needs to be shaped – a chicken-and-egg problem.

151 | See Hagelüken 2020.

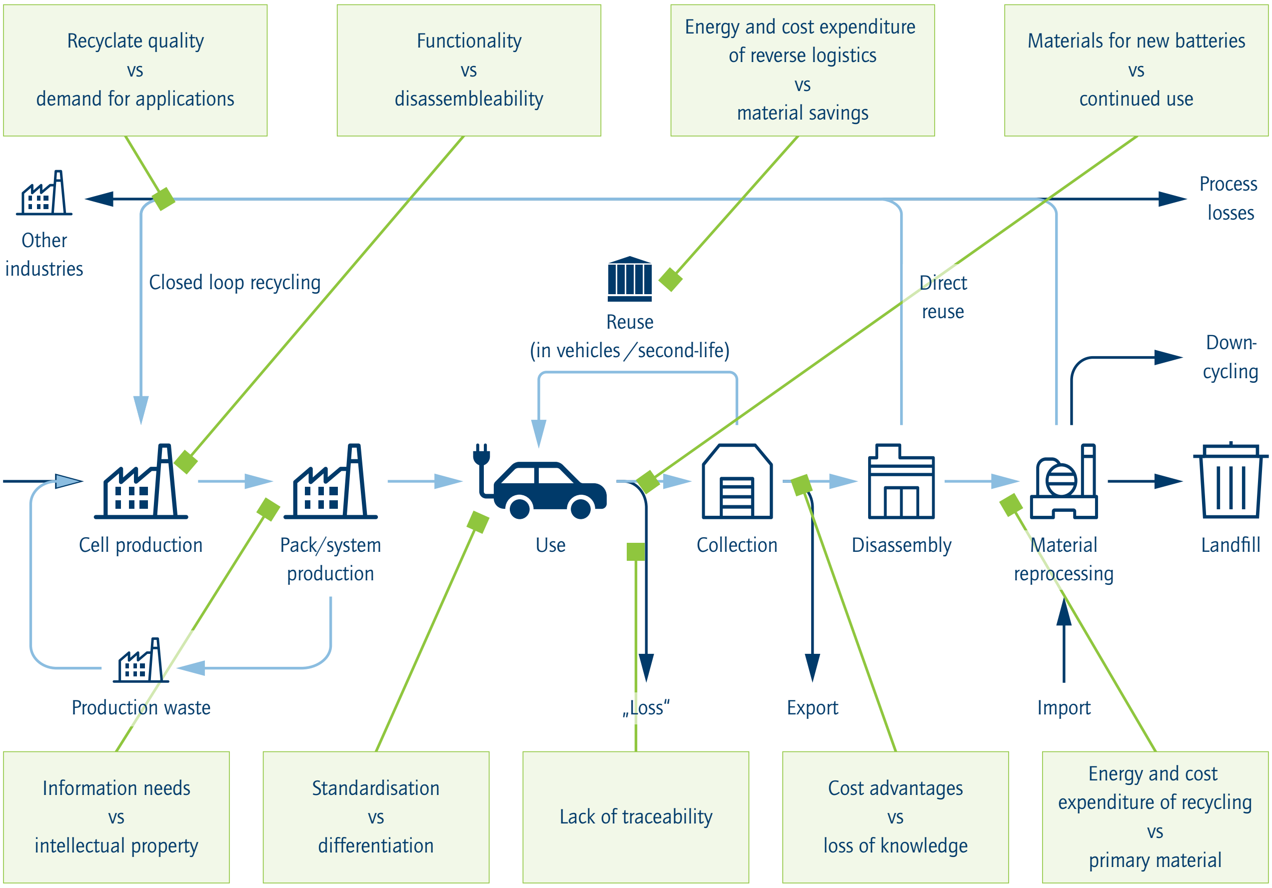


Figure 16: Conflicting goals in the value chain of batteries make a systemic approach indispensable (Source: own representation).

One of the tasks of the Traction Batteries Working Group was therefore to make conflicting objectives visible, discuss them, and work towards resolving and settling them (see Figure 16).

Within the framework of sub-working groups, numerous points were addressed in more detail, and proposals for their resolution were made both within the developed pilot profiles and between the sub-working groups (see chapter ý4, pilot topics and Annex I, pilot profiles I, II, II). Without claiming to be exhaustive, the following list is a collection of essential conflicting objectives and their treatment by the traction batteries working group:

The recommendations for action also reflect many of the findings on what adjustments are necessary to create a resource-productive and climate-friendly sector for traction batteries. However, many conflicting objectives will be addressed only in specific cases and under conditions that are not yet known. The Traction Batteries Working Group is laying some foundations to support the necessary developments.

Conflicting objectives	Addressed in particular by the work of
Information needs of individual actors in the value chain versus issues of intellectual property and data security (e.g. need for dynamic data on the performance of end-of-life batteries for second-life applications)	Sub-working group 1 "Understanding the service life of the battery"
Conflict between commercial or technical optimisation of battery performance, modularisation, and disassembleability for refurbishment and recycling (design for circularity), including shared incentives between vehicle manufacturers and end-of-life managers (dismantling companies, recyclers)	Sub-working group 1 "Understanding the service life of the battery", Sub-working group 2 "Model-based decision-making platform"
Material savings, security of supply, and environmental benefits through closed-loop recycling versus energy and costs for reverse logistics, recycling, and the like.	Sub-working group 1 "Understanding the service life of the battery" Sub-working group 2 "Model-based decision-making platform", Sub-working group 3 "Dismantling network for traction batteries"
Optimal environmental and economical handling, especially between second life and recycling, is mostly case-specific and basically unclear (e.g. still using critical metals in secondary applications over a longer period or producing new, significantly more powerful batteries)	Sub-working group 2 "Model-based decision-making platform" Sub-working group 3 "Dismantling network for traction batteries"
Need for optimisation between energy input and recovery as well as between optimal recovery of mass and quality of different target materials	Sub-working group 2 "Model-based decision-making platform"
Long battery lifetimes pose challenges for the profitability of necessary investments (through discounting, market dynamics, and innovations). Recycling and direct use of valuable raw materials in new batteries versus non-demanding second life	Sub-working group 2 "Model-based decision-making platform", Sub-working group 3 "Dismantling network for traction batteries"
Further conflicting objectives, for example regarding the best possible design of the process chain including handling in relation to energy requirements; interdisciplinary research and development on optimal environmental and economical handling, especially between second life and recycling.	Not or only indirectly addressed

4 Pilot topics of the working group

As has been made clear in the previous chapters, (incentives for) the provision of information and cooperation in this respect are critical in order to generate the maximum value from traction batteries for each value-added or life cycle step. Traction batteries are essentially both physical and digital products – they require advanced manufacturing technology, contain electrical charge from the day they are produced until the end of their life, and are completely digitally controlled. Their condition and thus (residual) value beyond the pure material value can be recorded only digitally. This makes corresponding (digital, electrotechnical and electrochemical) knowledge, tools, and methods – for example, for second-hand markets – indispensable. Not least because of their potential for danger and the high costs of manual dismantling work, the economic use of robotics and other automation technologies is also indicated at the end of their service life.

However, many of the technologies and standards required for this are still in their infancy; security recommendations, industry standards, interfaces, and tools are still missing.[152] There is also uncertainty regarding relevant regulatory systems, possible added value, and incentives. Finally, there is a lack of practical experience and empirical evidence for the concrete implementation of Circular Economy measures for traction batteries.

The pilot topics, which were developed by the Traction Batteries Working Group at the beginning of the work process, are intended to serve as a basis for decision-making for practical implementation and to highlight central open questions of a Circular Economy for traction batteries. The selection of the pilot topics was based on overriding decision criteria. In the final definition of the pilot topics, for example, care was taken to ensure that 1) the pilot topics make a significant contribution to achieving the target picture, 2) the competence spectrum of the working group members is included as comprehensively as possible, 3) new value networks and constellations of actors are initiated, 4) the projects can be implemented as quickly as possible, and 5) the projects have a scalable effect in terms of the expansion of a Circular Economy.

Based on the decision criteria presented, the working group decided to elaborate on the following three pilot topics. These were developed into detailed pilot profiles in the respective sub-working groups.

1. Understanding the service life of the battery
2. Model-based decision-making platform
3. Dismantling network for traction batteries

The practical added value of the three pilot profiles results from their consistent orientation towards successful implementation. Despite their specific thematic focus and design, all three pilot profiles have an overarching structure. Among other things, it addresses the current challenges in the system, identifies stakeholder groups relevant for implementation, explains operational and regulatory requirements, and concludes with the formulation of a concrete roadmap with recommendations for action and open questions.

In this respect, the pilot profiles can form the basis for further action by the actors addressed - for example, for the implementation of industrial projects, the tendering of public development or research projects, or the political shaping of regulatory frameworks.

In the following, the three pilot profiles are briefly summarised with respect to their core statements. The fundamental importance of the respective pilot project for the development of a Circular Economy for traction batteries will be clarified, core tasks and challenges will be specified, and content-related factors for a successful implementation will be outlined. Following this brief presentation of the individual pilot topics, the pilot topics will once again be examined with particular emphasis on their synergetic potential and interactions.

4.1 Understanding the service life of the battery

The objective of the pilot profile "Understanding the service life of the battery" is to provide a systematic overview of the provision of battery data (data availability) over the entire life cycle of the traction battery. The following summarising core statements of the pilot profile were derived in this context:

152 | See Bustamante et al. 2020. In addition to the adaptation of existing standards, the definition of new battery standards (e.g. in terms of performance testing, requirements for data formats, data availability, design, and security requirements) are essential. Among other things, the pilot profiles outline the first important starting points. Concrete recommendations for future standardisation activities will also be developed within the framework of the National Platform Future of Mobility (NPM)/Working Group 6: Standardisation, certification, and type approval and published as a "Priority Roadmap for Sustainable Mobility" by the end of 2020.

- The use of data and information from battery life cycles plays a central role in initiating and implementing cross-company and supply chain collaboration. Increased data transparency can clarify environmental (decarbonisation and social (responsible sourcing[153]) target parameters and increase the economic use potential of batteries (efficiency and availability of raw materials) over their entire life cycle. Transparent data availability thus makes a considerable contribution to overcoming the current relatively low level of consumer acceptance of the electrification of private transport.
- It is therefore necessary to make the data needs and requirements per process step and actor in the value chain transparent and to define the necessary standards of information in the sense of an IDIS (International Dismantling Information System) for Batteries. A basic distinction between "necessary" and "supplementary" data is proposed.
- However, data needs and requirements depend strongly on the business model chosen. For example, in the case of a leasing model in which the vehicle manufacturer or fleet operator remains the owner of the traction battery throughout its life cycle, data availability and traceability, the regulation of access rights, and the protection of confidential data are much simpler than in the case of "business as usual" in which ownership of the traction battery is passed on with each sale of the vehicle.
- Because, in principle, a lot of data on the condition of a battery is already present, but not necessarily available, a major challenge is to create incentives for all actors involved to share data. In particular, the availability of vehicle manufacturers' data on initial use and the corresponding battery behaviour has been identified as a key point. In this respect, the incentives for vehicle manufacturers to provide operating data must be increased.

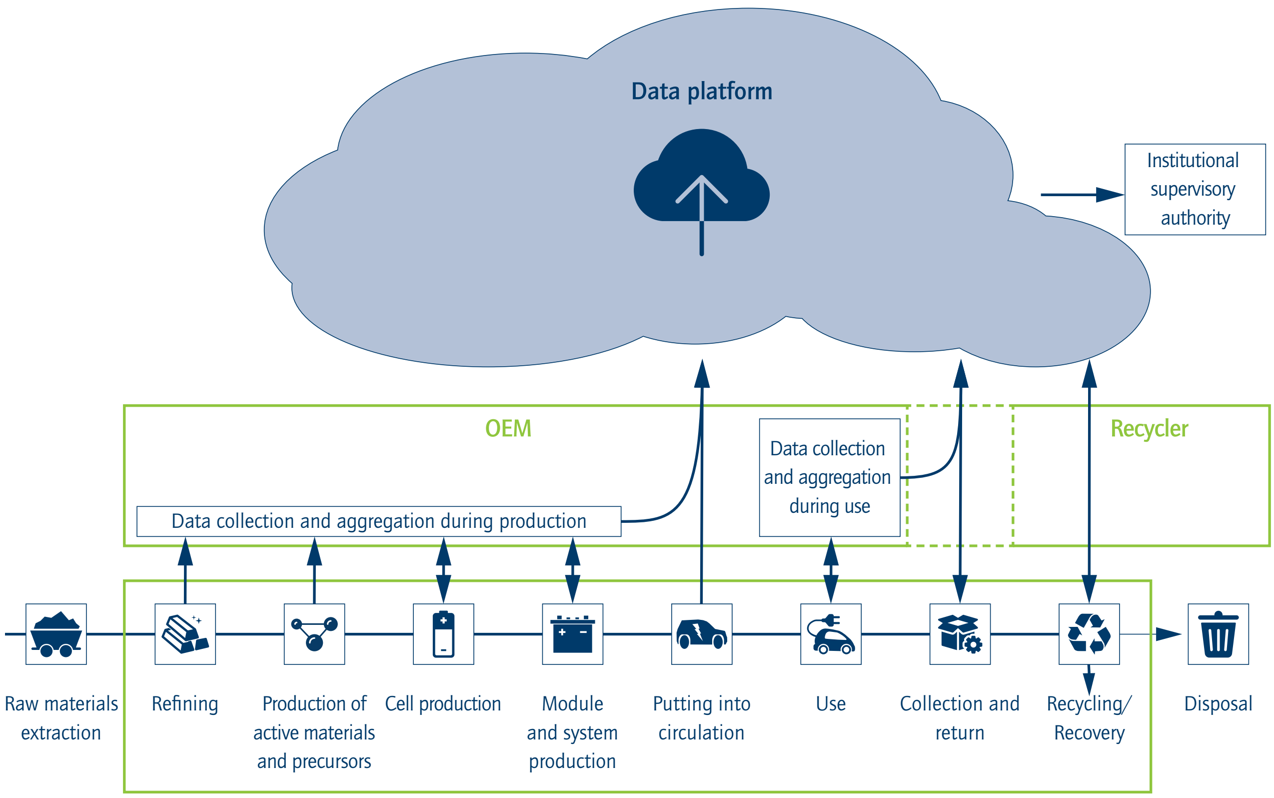
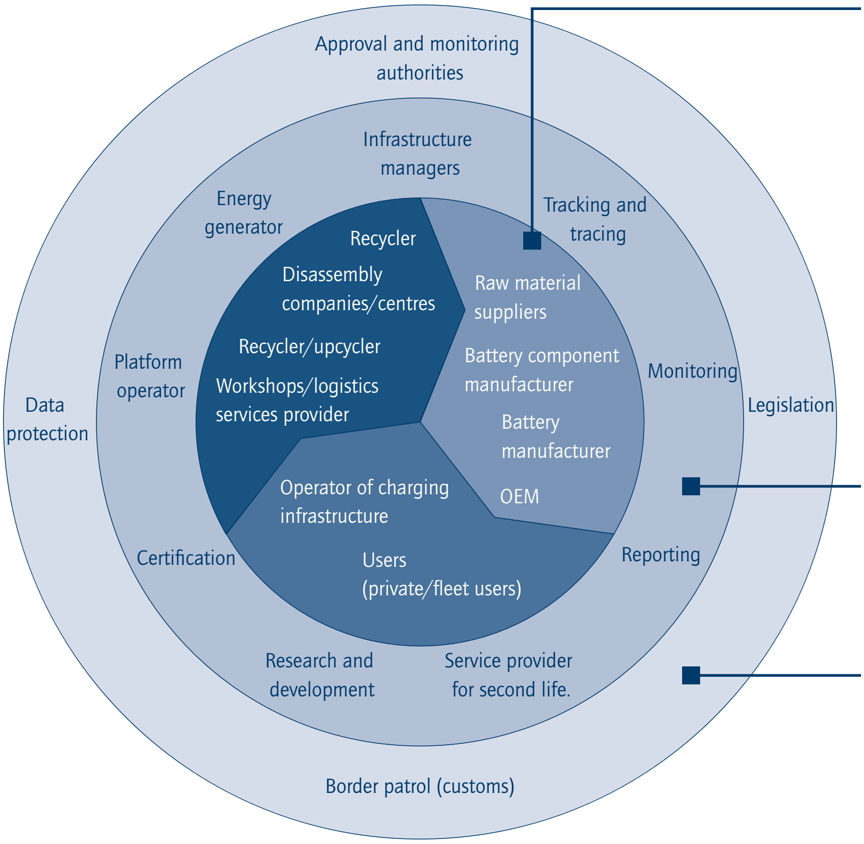


Figure 17: The core product of sub-working group 1 is recommendations concerning the information flows to promote the closed-loop recycling of traction batteries (Source: own representation, based on the representation of the World Economic Forum 2019)

153 | See glossary.



Product level

Manufacturer:
Data requirements: Raw material and supplier data
Incentive for cooperation: legal recycling quotas, security of supply, responsible sourcing

Users:
Data requirements: Condition data
Incentive for cooperation: Performance enhancement/financial incentives

Recycler:
Data requirements: Usage data, condition data
Incentive for cooperation: Data access for recycling data

Data level

Data requirements: Manufacturing data, usage data, condition data, recycling statistics
Incentive for cooperation: Implementation/expansion of internal business models

Regulatory level

Data requirements: Exports and imports; enforcement monitoring and Circular Economy indicators, macroeconomic statistics and trends
Incentive for cooperation: Inspiration for cooperation only necessary for private sector actors

Figure 18: Actors, data needs, and incentives for cooperation for a pilot implementation (Source: own representation)

Time horizon / Work package	short term												medium term	long term
	2021				2022				2023				by 2027	by 2030
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4		
Basis for traceability of fate over the life cycle			■	■	■	■							Data integration and protection (data and IP protection, integration in data platforms); definition of reporting requirements;	European and global harmonisation of data integration, reporting, and monitoring
Definition of data requirements and their availability	■	■	■	■	■	■	■	■						
Basics central data platform (+ access and protection)	■	■	■	■	■	■	■	■	■	■	■	■	Development of a reporting and monitoring system (including big-data analyses) in coordination with business and politics (and integration into EU projects)	
Development of an interoperable data platform + necessary standards				■	■	■	■	■	■	■	■	■		

Figure 19: Most important steps for the implementation of the project description "Understanding the service life of the battery" (Source: own representation)

With regard to the concrete design of the data platform to be implemented, a number of fundamental questions arise with respect to: data storage (what are the advantages and disadvantages of local versus central data storage?), role-based data access (which actor has which read and write rights?), and data transparency (who created or modified which data and when?). In view of the large number of data providers and users, the interoperability of data should be guaranteed by uniform standards.

4.2 Model-based decision-making platform

The objective of the pilot profile "Model-based decision-making platform" is to provide a decision basis for an open platform for modelling the optimal use of batteries at the end of their life cycle. The following summarising core statements of the pilot profile were derived in this context:

- Model-based decision support contributes to optimised decision making (second life or different recycling routes) for the treatment of used traction batteries.
- The goal is the overall, optimised design of the battery life cycle or the network of all actors and the fair distribution of expenses and revenues.
- Standardised and valid system boundaries and calculations lead to transparency and comparability, taking into account economic, environmental, and social aspects.
- The model-based decision support must be based on real and validated data and must consider exergy losses and achievable output qualities in the various end-of-user and end-of-life options in a transparent manner.
- Many stakeholders involved throughout the life cycle of traction batteries have important information for optimised life cycle planning. It should be possible to collect this information on the platform and make it available for value-adding activities. It is always important to securely store sensitive data.

A precise design of the platform is operator-specific and depends, among other things, on the chosen business model and the actors considered. It also requires further research with regard to the further development of the integrated models.

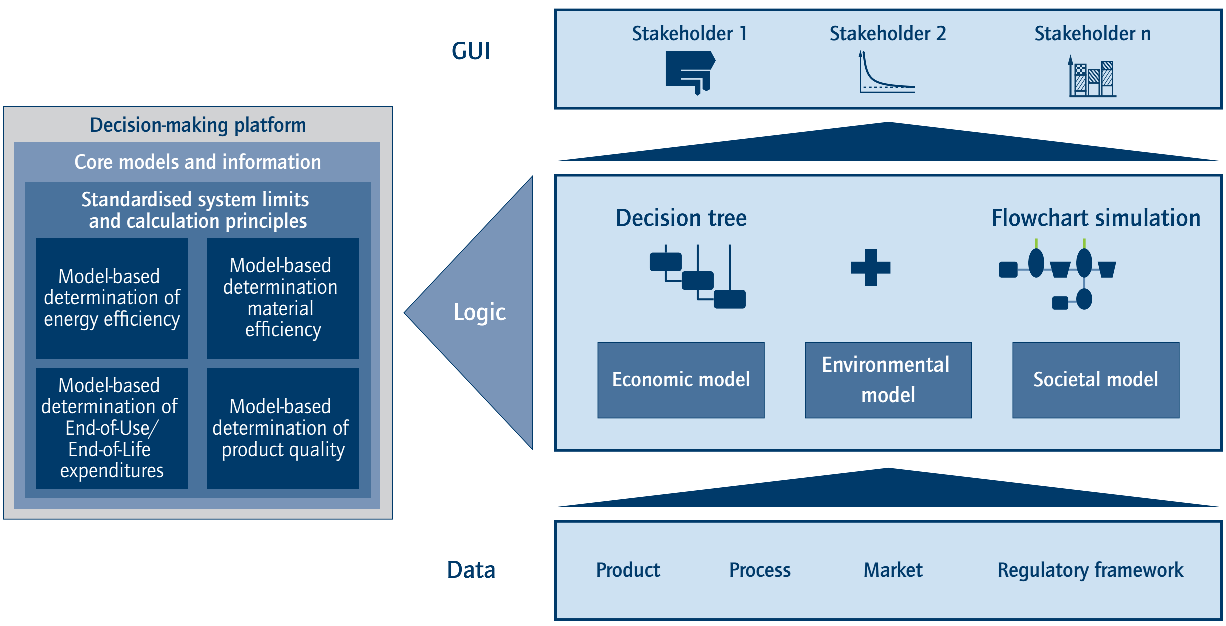


Figure 20: Model structure of the decision-making platform (Source: own representation)

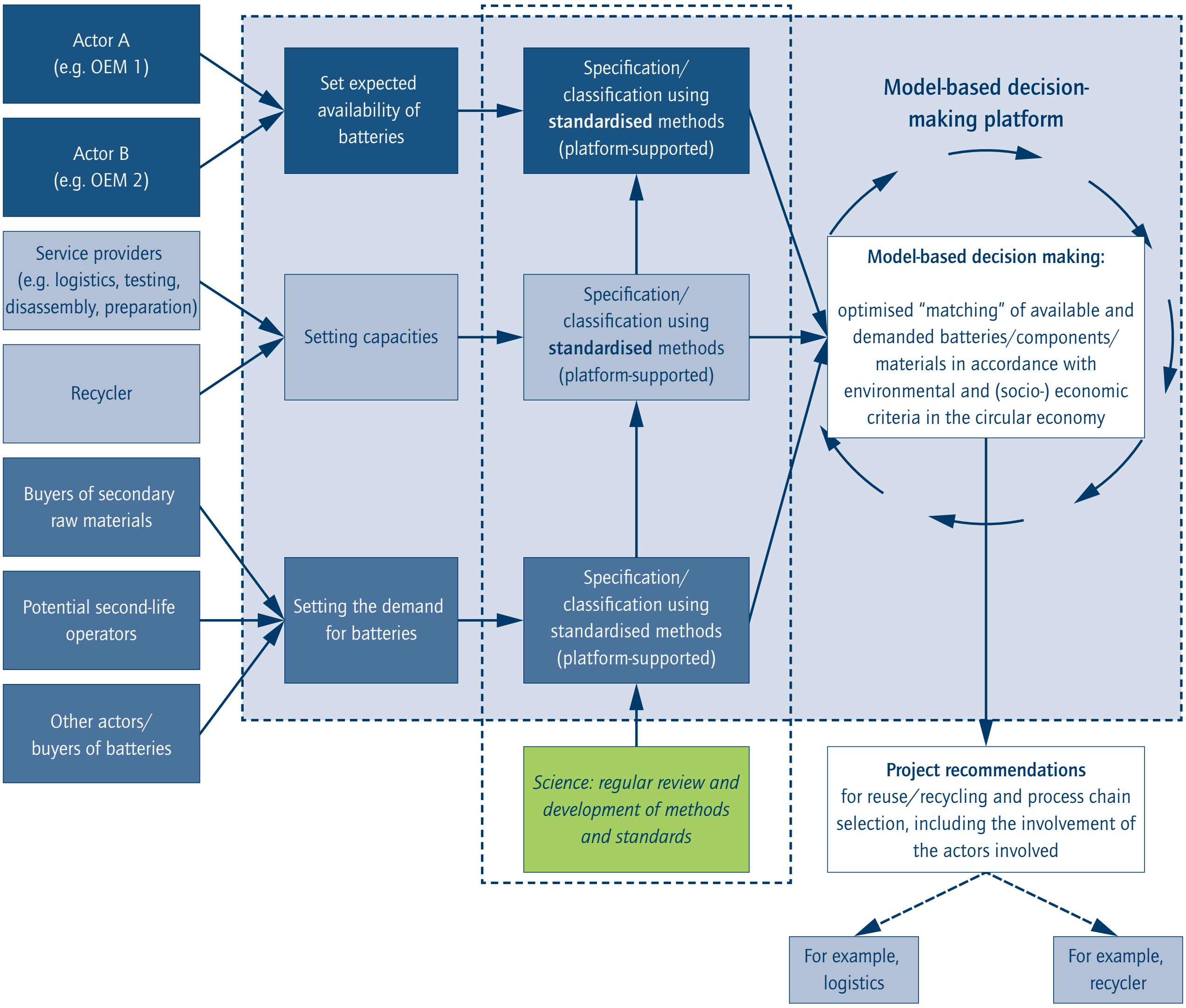


Figure 21: Schematic representation of the integration of a platform into the business processes of the Circular Economy (Source: own representation)

Time horizon	Horizon 1												Horizon 2	Horizon 3
	2021				2022				2023				by 2027	by 2030
Work package	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4		
WP1: Development of demand and price forecasts for first- and second-life applications as well as battery materials in Europe by 2035													Identification of possible business models and development of a platform operator; targeted support for a decision-making platform, including financial support for prototyping; development of an incentive system for circular value creation in networks	Completion/further development of models; implementation of the decision-making platform; involvement of other actors
WP2: Definition of international/European calculation standards, system boundaries, and key figures for the assessment of end-of-use/end-of-life scenarios														
WP3: Conceptual development of a platform for different operators														
WP4: Model-based determination of the energy efficiency (including exergy losses) of various process routes														
WP5: Model-based determination of the material efficiency of various process routes														
WP6: Model-based determination of necessary expenditures and achievable product qualities of different end-of-use/end-of-life applications														
WP7: Development of user-friendly, compressed calculation and visualisation methods														
WP8: Development of the roadmap for a decision-making platform for traction batteries in Europe by 2035														

Figure 22: Possible roadmap of the model-based decision-making platform (Source: own representation)

4.3 Dismantling network for traction batteries

The objective of the pilot profile “Dismantling network for traction batteries” is to outline a “project plan” to implement a European dismantling network. The following summarising core statements of the pilot profile were derived in this context:

- The establishment of a Europe-wide network of efficient dismantling facilities for traction batteries is essential for the success of the entire recycling or reuse chain. The entire network is an important link between collection (e.g. authorised workshops) and further treatment/recycling (or second life) of the battery modules.
- The core task of a dismantling network is therefore to examine large numbers of batteries for their suitability for second life as well as to dismantle batteries not suitable for second life down to the module level with the necessary infrastructure.
- When implementing such a dismantling network, however, the following paradox (chicken-and-egg problem) must be resolved in the transitional period: On the one hand – as long as there are still very few end-of-life batteries of electric vehicles – the incentive for potential operators is low. On the other hand, a small number of dismantling facilities in Europe means that the specific logistics costs and CO_2 emissions of transport are quite high simply because of long transport distances.
- A critical success factor for the implementation is to make well-founded investment decisions for new dismantling facilities in order to improve the recycling infrastructure to fit the needs of the industry and make it scalable at the European level. Certain parameters must be considered. These include timing, choice of facility location, dimensioning of the facility size according to the future increasing return volumes, and specification of the facility equipment (degree and adaptability of automation with regard to changing battery formats and compositions).

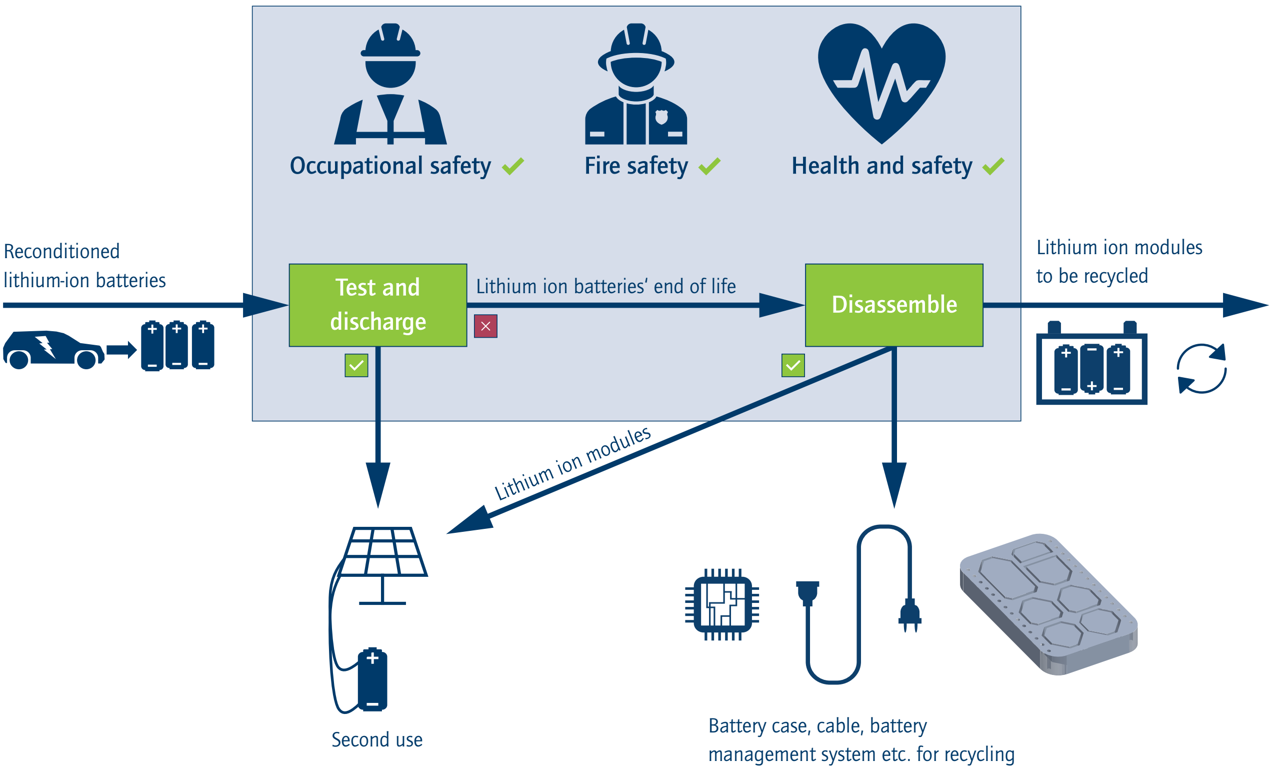


Figure 23: Concept of a dismantling facility for traction batteries (Source: own representation)

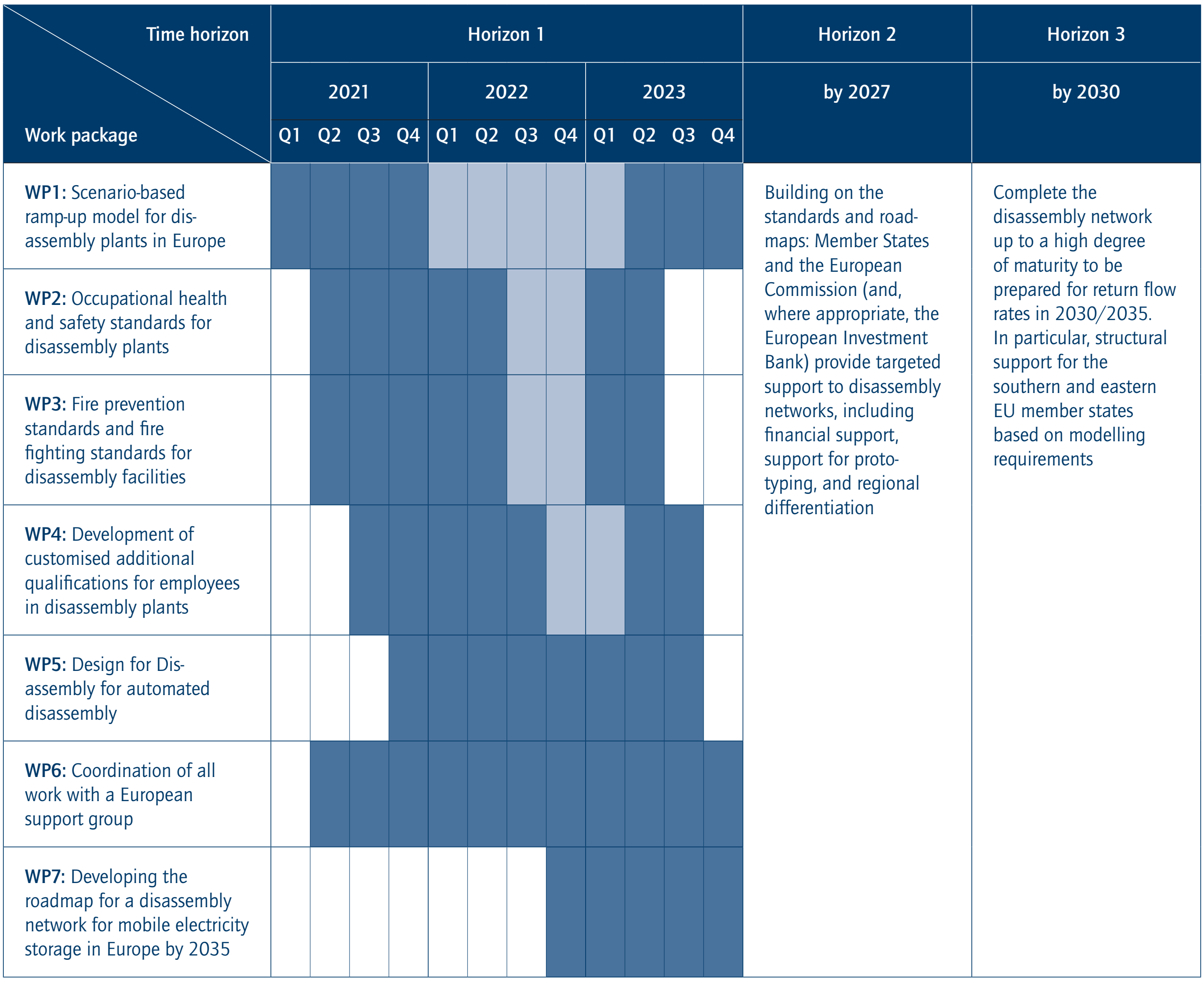


Figure 24: Possible implementation steps for the establishment of a Europe-wide dismantling network (Source: own representation)

The modern, preferably automated disassembly (based on a forced design for disassembly) of high-voltage batteries in facilities that meet high fire, occupational health, and safety requirements and which are operated by highly qualified personnel must become an important brand core of the recycling industry in Europe.

4.4 Integrated consideration of the pilot profiles

From the summarised presentation of central core statements of the three pilot profiles, it becomes clear that the various pilot projects are partly interdependent and can therefore fully develop their synergetic potential in an integrated view only.

In principle, the provision of data must be considered a basic prerequisite for the successful implementation of all three pilot projects. Only if sufficient data (static and dynamic) are available for the entire life cycle of the traction battery (see pilot topic "Understanding the service life of the battery") and further interpreted against the background of market-related information and regulatory framework conditions will the necessary inputs for a model-based decision regarding the optimal use of batteries at the end of their life cycle be available (see pilot topic "Model-based decision-making platform"). The outputs generated from

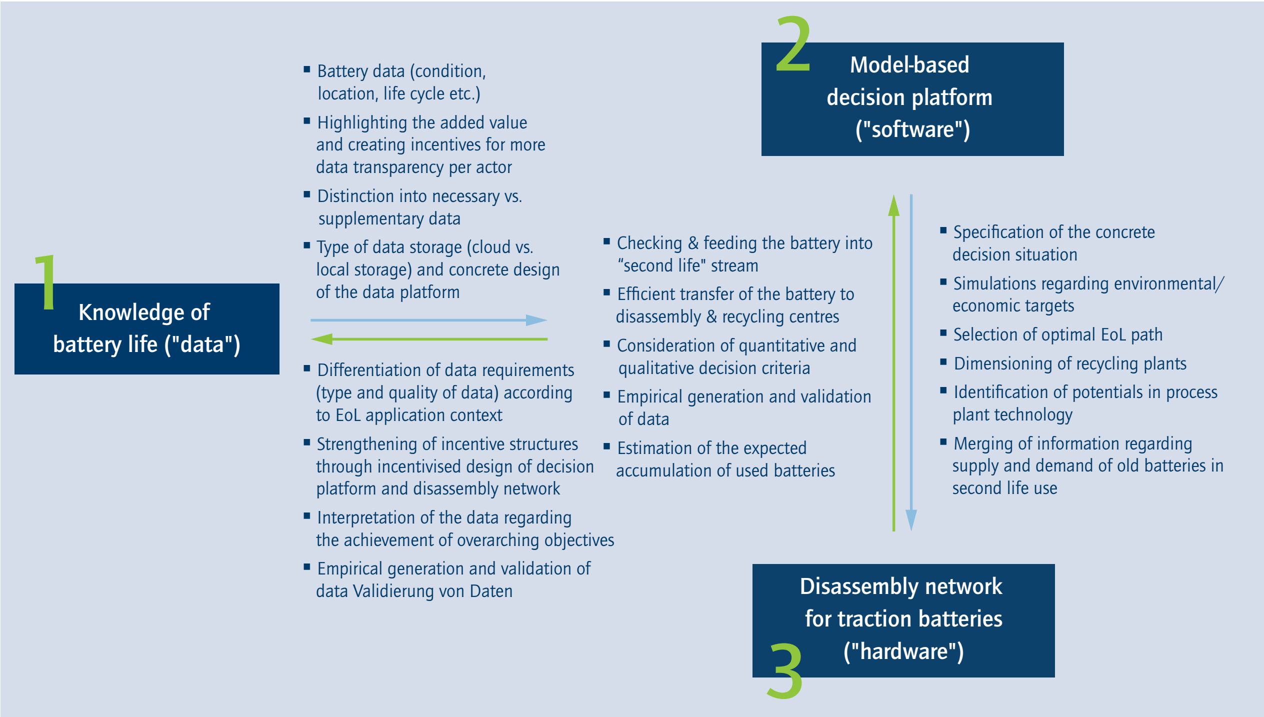


Figure 25: Interactions and synergies between the pilot topics (Source: own representation)

such a decision-supporting process can, in turn, help the operators of dismantling facilities or networks to better determine, for example, the dimensioning of planned recycling facilities and to substantiate concrete investment decisions with a solid data base (see pilot topic "Dismantling network for traction batteries").

There are also interdependencies between the pilot topics in the opposite direction of action. For example, the concrete design of dismantling networks can help to collect and pass on dynamic battery data at critical nodes. Similarly, the concrete design of the decision-making platform can influence whether there are specific incentives for individual actors to share relevant data. Figure 25 illustrates these recursive interactions and synergies between the pilot topics by means of selected content. For a better understanding, the three pilot topics are heuristically differentiated in their respective focus with regard to "data", "software", and "hardware".

5 Recommendations for action for a Circular Economy for traction batteries

With the aim of realising their vision and facilitating the transformation to a Circular Economy, the members of the "Traction Batteries Work Group developed recommendations for action for politics, industry, and the scientific community. The recommendations for action for politics focus on the dimension of "regulatory systems". They also strengthen the possibility of collaborative action between actors (value networks) by creating unified conditions for competition (level playing fields) and offering planning security for the initiation and implementation of new business models. The recommendations for action for industry focus on bringing Circular Economy technologies and business models to the market and scaling them within collaborative value networks. The recommendations for action for the scientific community aim to apply sound scientific expertise to politics and business and help the relevant actors make objective decisions based on the latest technical advancements.

The recommendations are the result of the discussions of the working group and its sub-working group as well as individual consultations. Unless otherwise indicated, they represent the common positions of the members of the traction batteries working group. Prioritised core elements are also set out in Chapter 6 of the General Report along a roadmap.

5.1 Recommendations for action for politics

As a central actor, the German legislator is called upon to provide ambitious incentives in the European process. In both the European and national context, the range of resource policy instruments (i.e. economic, regulatory, and informational as well as education and research) should be used to accelerate the transformation towards a Circular Economy.

The members of the Traction Batteries Work Group and the office of the *Circular Economy Initiative Deutschland* offer to support this process with their expertise.

- **Clear and binding definitions and standards** for the creation of a level playing field are necessary – for example, to enable consistent reporting or to assess the eco-efficiency of end-of-life (EoL) processes. The legislator should launch activities/initiatives – including on the:

  – Establishment of central **definitions**: e.g. clear legal definitions of vehicle batteries, unambiguous description of system boundaries relevant for legally binding target values (see in-depth study on battery recycling), and standardisation of the calculation of carbon footprints for relevant elements (e.g. recyclates, primary materials, and battery systems).
  – Introduction of **minimum standards**: These should include both enabling and protective parameters (in particular data protection, occupational health and safety, and mandatory recovery rates). For this purpose, legal and technical assessments must be obtained.
  – Support of **industrial standards** in consultation with industry – for example, by using and (where appropriate) mandating the established standards and standardisation organisations.
  – Consideration of **data and IP security** as well as innovation effects. This should be done using state-of-the-art technologies such as block chain and end-to-end encrypted data transfers and databases.

  These points are to be shaped at EU level in cooperation with the other member states and supported by the national legislator and implemented nationally.

- The legislator should clearly define the **rights and obligations** of relevant actors within a circular battery value chain, taking into account cost-benefit effects and fair distribution of the these – among others:

  – Definition of **reporting obligations**: What is to be reported must be defined taking into consideration costs/benefits. At the very least, however, this should include the origin, environmental and human rights effects of the battery materials and substances used, safety-related data, and the whereabouts of the batteries at the end of their life.
  – Specification of **minimum standards in the circular battery design** of the manufacturers, including under the Ecodesign Directive.[154]
  – Clarification of **liability and warranty rules as well as return and take-back obligations** between manufacturers

154 | See Europäische Union 2009.

and potential second life users. In particular, there should be the possibility of passing on the vehicle manufacturer's **EPR obligations** to other users (especially for second life) after the batteries are certified as suitable for this purpose at the end of their first life.
– Introduction of **a second life duty of proof** for the use of a battery in further or converted use (refurbishment/second life) to ensure the **transfer of EPR obligations** and the subsequent **liability** of second life users in order to prevent leakage.
– **Appropriate and effective incentives** (for the acceleration of electromobility, Circular Economy business models, and the achievement of key metrics) **and sanctions** (for non-compliance) must be defined and implemented within the framework of the European regulatory system. The introduction of **deposit systems** should be examined in particular (see in-depth study on deposit systems).
– Successive **development of sanction mechanisms** to ensure the efficient implementation of the measures ("Smart" Policy) – see the following **"Sanctions"** bullet point.

These points are to be shaped at EU level in cooperation with the other member states and supported by the national legislator and implemented nationally.

- In order to ensure the follow-up, adjustment, and further development of the transformation towards a Circular Economy, it is important to **create a central institutional sponsor** that, based on systemic technical expertise, will carry out continuous data monitoring, compile and validate (success) statistics and forecasts, and determine and further develop indicators on the degree of circularity.

  – This function can also be integrated into existing institutions such as the Federal Environment Agency in order to prevent redundancies and conflicts. It is important to have the appropriate technical expertise and the authority to demand reliable data and to carry out relevant evaluations (including sanctions). An analogy could be sought in the mining office, for example.

  This must be implemented by the national legislator. The creation of a corresponding actor at the European level should also be considered.

- Development of offers for education and training as well as rapid application of **basic and applied knowledge,** which enable the scaling of the Circular Economy in cooperation between politics, business, and science. This includes:

  – Integration of the Circular Economy in the **curricula** of general and especially vocational schools;
  – Consideration of the Circular Economy in relevant **training occupations** (for example, for the safe handling of high-voltage systems);
  – Establishment of Circular Economy-related **courses of study and in-depth studies** (in the dual education system and universities);
  – Creation of **learning factories** for the Circular Economy; these can be integrated as realistic environments for professional training, teaching, and research.

  This is to be shaped both at the level of the European Union and by national legislators; in Germany at the federal and state level.

- Strengthening and significant expansion of research and development in the field of the Circular Economy, in particular traction batteries; this will ensure rapid implementation and successful closed-loop recycling. This includes in particular:

  – Anchoring in research framework plans and development of Circular Economy related **funding announcements** as well as provision of the necessary funds for supporting collaborative projects;
  – Establishment of Circular Economy related **professors/chairs;**
  – Expansion of the **research infrastructure** at universities and non-university research institutions;
  – Provision of funds for the **transfer of research results** into innovative implementations;
  – Establishment of a **technical advisory board** with members of all affected stakeholders to develop and advise on support concepts and measures.

  This is to be shaped both at the level of the European Union and by the national legislators; in Germany at the federal and state level.

- The legislator should offer all actors in the value chain an evaluative orientation. To this end, it must develop measures to increase transparency in the industry and for consumers:

  – Increasing **transparency for consumers**: At the battery level, this could include, for example, the introduction of labels on the eco-social performance of the battery (e.g. carbon footprint per performance, recycled content, and human rights due diligence).

– Increase of **data availability for economic actors**: The digital provision of business-relevant information (e.g. notes on safe handling, on materials contained, including the proportion of recycled materials, on the carbon footprint per output (kilogram CO_2 equivalent per kilowatt hour), human rights due diligence) should be ensured by the legally binding description of **material or product passports (Battery Passport).**[155, 156, 157]
– Determination of the **mandatory data to be reported:** These are to be subdivided into **static data** (e.g. material footprint, serial numbers, and production information) and **dynamic data** (e.g. the respective owners, maintenance measures, and state of health (SoH)). Selected data of high relevance for the entire market and public actors should be stored in centrally managed databases **(data spaces)**[158] while ensuring data protection and security.
– Creation of **certification options for high quality products and processes**: At the process level, for example, this could mean certifying individual actors for high-quality business activities (e.g. with regard to dismantling, transport, second life, or recycling).

These points are to be shaped at EU level in cooperation with the other member states and supported by the national legislator and implemented nationally.

In-depth study IV: Battery recycling: Definitions, differentiated goals, and levels of ambition

Generally accepted and precise **definitions** of key terms such as battery recycling and recyclate are important bases for the calculation and assessment of recycling efficiency and setting recovery rates. Because of the joint comprehensive expertise of the working group members and the relatively established, engineering-technical/physical processes of battery recycling, more concrete recommendations can be made here than for other topics mentioned in this report. **The following definitions, developed by the members of the working group on the basis of their expertise along the entire value chain and validated by external experts, are recommended**:

- **Battery recycling**: the entire process from the deactivation of the battery (components) to the completed extraction of raw materials ready for sale (recyclates) for the production of new battery materials of comparable quality to the primary material (see Figure 26 for the system limits of battery recycling selected here):
- **Return or collection rate:** Percentage of traction batteries compared with batteries placed on the market that can be shown to have been collected for recycling or, where applicable, reuse or reuse in second life after decommissioning. The collection of second-life batteries at the collection of their end-of-life (EoL) should be done separately to avoid double counting.

The experts of the working group recommend mandating a return or collection rate that is as complete as possible (close to 100%). This is the first indispensable step in end-of-life (EoL) management and has a very large effect on all downstream steps.[159, 160] In order to achieve this ambitious target, which is based on the current returns of vehicles with combustion engines, further measures will be necessary. The working group also makes recommendations in this respect.

- **Recycled material:** secondary raw material recovered by recycling (especially metals such as cobalt and materials from active materials) of comparable quality to primary raw materials; this can be used for the manufacture of new products.
- **Recovery rate**: yields/recovery rates related to the overall battery recycling process. The recovery rate describes the quotient of the mass of the physically reusable recyclate and the input mass in relation to the overall recycling process, usually material-related; accordingly, the return or collection rate is not to be included in the calculation. To be collected as the average over a financial year of an operational unit

155 | See glossary.
156 | See Europäische Kommission 2020.
157 | See Presse- und Informationsamt der Bundesregierung 2019.
158 | See Europäische Kommission 2020.
159 | See the call for the establishment of return quotas in ProgRess III.
160 | See Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2019.

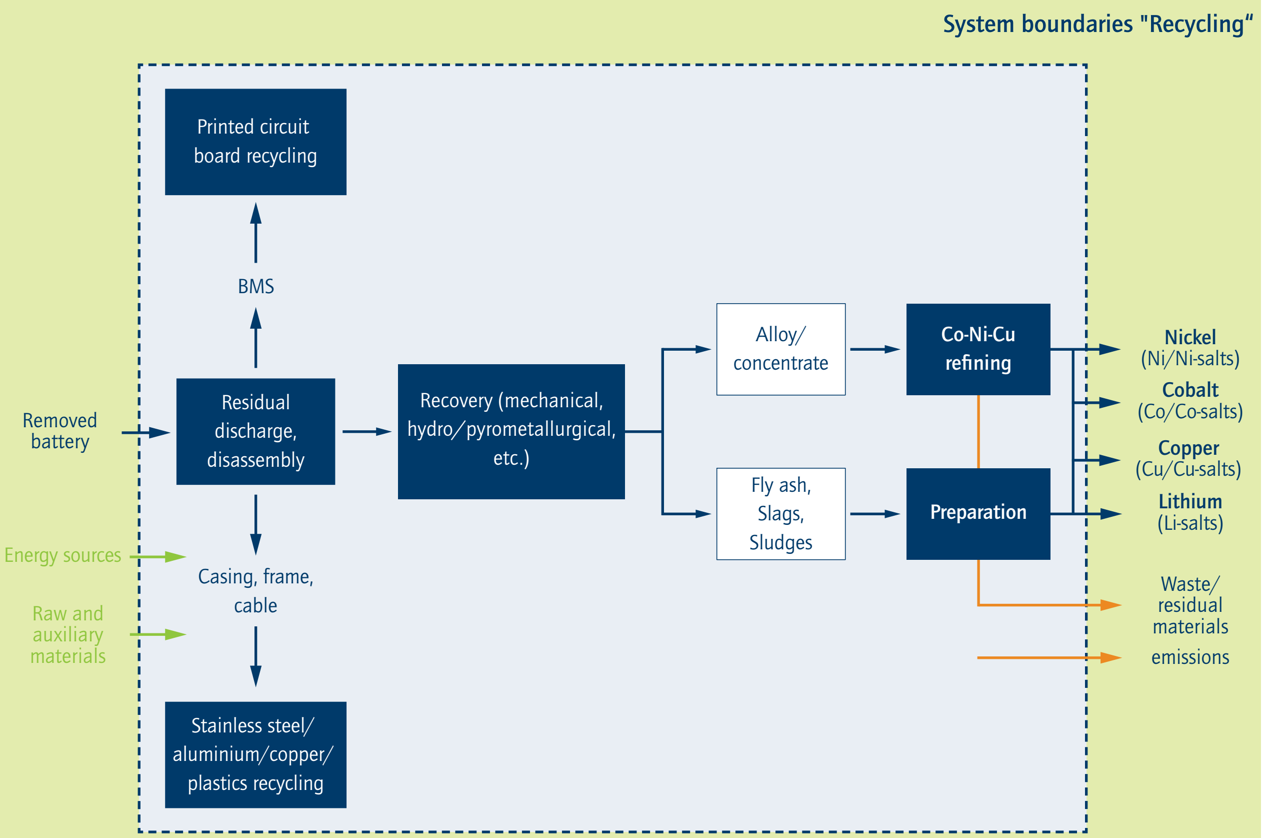


Figure 26: System boundaries of battery recycling (with essential processes and materials) (Source: own presentation, based on Buchert et al. 2011)

(recycling site, business unit, or recycling process) and verified by appropriate audits or certification for quantity, quality, and energy or carbon footprint.

Thus, the calculation of the recovery rate covers the **entire recycling process** – whereby **earlier steps in the process reduce the remaining maximum success rate and are therefore of high importance for the overall success**: *(1 – dismantling and treatment losses) * (1 – metallurgical[161] losses) = recycling rate*

If the use and collection phase is included, the following end-of-life (EoL) yield results: *(batteries put into circulation) * (return rate of EoL batteries) * Recycling rate = yield*

As a rule, the calculations should be carried out for each substance.

The following points must still be observed:

- In addition to the definition of **binding minimum recovery rates or recycling quotas**, **differentiated material-specific quotas** for the most relevant materials and substances are important – i.e. according to the EU definition, "critical" and particularly CO_2-intensive functional metals and substances that are particularly important for battery production.
- The targets should be **ambitious** and **increase** over time in line with the development paths of the industry – for example, based on the Best Available

161 | See glossary.

Technology (BAT) approach.[162] They should continue to be reassessed at appropriate intervals.

- The high quality of the recyclates should be emphasised: Thus, a) recyclates are of no great value if they are not of high quality (downcycling) – missing requirements for recycled qualities allow (and thus possibly reward) low-quality recycling, which is not desirable from the point of view of a Circular Economy, b) only by means of high-quality recycling processes can a far-reaching decoupling of resources be achieved (do not optimise for short-term economic efficiency and energy balance in the existing energy mix), c) under medium-term pricing of CO_2, higher-value recycling moves closer to a macroeconomic optimum so that early regulation is in line with far-sighted policy.
- In the future, recovery rates should be supplemented by an assessment of the recovery in accordance with **systemic thermodynamic evaluation** (i.e. their effect on the exergy or entropy of the overall system).[163, 164]
- In order to be able to consistently determine the (generally positive) environmental effects of the resulting recyclates in comparison with each other and with comparable primary materials, the recycling processes should be evaluated beyond the recycling rates achieved, primarily according to their energy and/or CO_2 intensity as well as (if necessary) according to other environmental factors, and the effects should be allocated to the recyclate.
- If recycled battery materials are used in other high quality products (open loop), it must be demonstrated that this has an overall positive or at least neutral effect on system efficiency and that the recovered materials are of an appropriate quality as defined in this report.
- An embedding of the aforementioned points in the EU Directive (EU) No 493/2012 ("Battery Directive"),[165] an explicit extension of the Directive to lithium-ion traction batteries, and a specification in this regard are to be aimed for. Harmonisation of implementation by different EU member states should also be supported.

Material	Recommended Recovery rates*	
	2025 – binding	2030 – to be aspired to***, ****
Total battery**	60 %	70 %
Lithium	50 %	85 %
Cobalt	85 %	90 %
Nickel	85 %	90 %
Copper	85 %	90 %
Steel	90 %	95 %
Aluminum (without Al foil)	90 %	95 %

* is determined over the entire recycling process excluding collection or return (see Figure 26 in the general report), in battery quality or comparable. The recovery of organic components should be designed to optimise the exergy of the overall process and only secondarily according to mass yield and not at the expense of the recovery of high-quality recyclates of the important battery materials. Return losses must be accounted for additionally and minimised accordingly.

** The proposed recovery rates for the total battery should be set flexibly because organic and volatile substances (electrolyte, plastics, graphite) account for a significant proportion (about 30–40%). These can often not be recovered in adequate quality or only at great cost, which could be at the expense of the energy balance and yield of important battery materials. Because the latter are given priority, strict minimum values for the entire battery or individually for electrolyte, plastics, and graphite are unlikely to be considered appropriate. Their recovery should only be aimed at by ensuring the overall energy balance and recovering important battery materials in high quality.

*** In the view of Agora Verkehrswende and the Oeko-Institut, under regulatory premises and for reasons of investment security, it is preferable to also make the values for 2030 binding and, if necessary, to subject them to revision.

**** Based on work for the European Commission in preparation for the revision of the EU Battery Directive, the Oeko-Institut believes that more ambitious 5% higher values for cobalt, nickel, and copper for 2025 and 2030 are achievable in terms of industrial best practice. These values should be checked regularly and, depending on technical progress, also be adapted in the legal requirements.

Table 2: Recommendations of the Traction Batteries Working Group on recovery rates to be made mandatory or to be aimed at (taking into account the related definitions)

162 | See OECD 2017.
163 | See Reuter et al. 2019.
164 | Note: For justified reasons, this does not correspond to the thrust of the current revision of relevant regulatory systems – especially the Battery Directive – but should be taken into account in the future.
165 | See Europäische Union 2012.

- Like other regulations supporting the Circular Economy, the above measures are to be applied to all traction batteries placed on the EU internal market, regardless of their origin or that of their producers.

Taking into **account the definitions, system limits and further explanations specified here, the members of the Traction Batteries Working Group recommend the following recovery rates** (see Table 2). These were derived based on current scientific research[166, 167] as well as corresponding empirical values from current industrial and scientific practice through detailed discussion of the participating experts and validated by external experts. **The material recovery rates represent ambitious yet commercially actionable values – taking into account the entire recycling process** (see Figure 26) **and the high-quality recovery of the combination of materials mentioned.**

They are therefore *lower* than many values found in the literature, which often only reflect parts of the recycling process or laboratory values.[168] The proposed values refer to the years 2025 and 2030 according to the time horizon of the Traction Batteries Working Group. While the short-term values should be considered binding in order to ensure the effectiveness of the ambitious policy measure, the recommendation of the members of the working group for the long-term values should only be aimed for. In the future, it should be reassessed whether a further binding increase in the values is worthwhile – depending, for example, on future technical developments and process-related and political optimisation goals.

- The **harmonisation of national and transnational regulatory systems** by the legislator is urgently recommended on several issues, for example:

  - **Processes and requirements for cross-border transport** of end-of-life (EoL) traction batteries and components
  - **Definitions of central terms** (such as recycling – see in-depth study on battery recycling –, waste definition, "end of waste", ownership status)
  - **Disclosure requirements and accreditation options for key metrics** (e.g. the carbon footprint or the recycled portion of the battery)
  - **Harmonisation of battery-relevant regulatory systems with related legislation** such as energy market, infrastructure, product and mobility regulation, taking into account life cycle effects (e.g. facilitating the use of battery electric vehicles (BEV) and stationary battery storage as "virtual power plants in electricity grids in Germany as well as harmonised EU energy markets)

  These points are to be shaped at EU level in cooperation with the other member states and supported by the national legislator and implemented nationally.

- **Targeted economic and scientific promotion** of the Circular Economy is recommended. This includes, in particular, the support of concrete projects for the (further) development of technologies and business models relevant to the Circular Economy and for ensuring the necessary knowledge build-up, especially in small and medium-sized enterprises (see Section 5.3 Recommendations for action for the scientific community).

  This is to be arranged by the national legislator, taking into account restrictions under European law and ideally in cooperation with the EU and member states.

- The formulation of appropriate **incentive systems and sanctions** must also be considered by the legislator:

  - Here, a **balance** must be **maintained between effectiveness (**increasing environmental friendliness and strengthening economic and innovative power, for example by automating Circular Economy measures) **and efficiency;** the possibilities for differentiation and competition between the economic actors involved must also be taken into account.
  - The application of more extensive **economic incentive systems and appropriate sanctioning procedures** for the (over)attainment or failure to meet recycling targets (bonus/penalty) should be considered. These include, for example, more extensive tax relief, burden sharing procedures, and the imposition of fines for non-compliance.

  These points are to be shaped at EU level and supported by the national legislator and implemented nationally.

166 | See Peters et al. 2017.
167 | See Miedema/Moll 2013.
168 | cf Melin 2019b.

In-depth study V: Measures to increase return quotas: Financial incentive systems – Focus on deposit system

Because of the size, material value, and hazard potential of traction batteries, the probability that they will remain unused for a longer period of time after their end of life is low compared with other products. However, there is a risk that – as is currently the case with end-of-life vehicles (ELVs) – spent battery vehicles or batteries will be exported from Europe via dubious channels and thus removed from the cycle (leakage). Additional measures are likely to be necessary to reliably ensure high-quality reuse and material recovery.

While "soft" measures such as education campaigns usually have limited success in increasing product return rates, deposit systems (as one example of financial incentive systems) have, in many cases, shown an effective steering effect. Although a direct transfer from experience in other product segments (e.g. low-value and comparatively short-lived products such as small batteries, electronic scrap or beverage packaging) to high-value, long-life products such as traction batteries is not readily possible, there are many indications that a deposit system for lithium-ion traction batteries could be effective in reducing this leakage and thus increasing return and collection rates.[169] Changed ownership models such as car or battery leasing models could also increase return or collection rates because the responsibility and options for action would remain directly with the producers. However, until these have become widespread practice, deposit systems could be a way of collecting end-of-life (EoL) traction batteries and reliably returning them to the cycle.

The design of such a model for traction batteries must be examined in more detail:

- As experience with the large number of existing deposit systems for different products shows, depending on the deposit amount and user-friendliness, a deposit can be an effective and efficient way to create incentives for consumers to return end-of-life (EoL) products to the manufacturer and thus to ensure that these products are fed into suitable recycling channels.
- In order to provide a sufficient incentive to return the battery, the high value of the traction battery may require a correspondingly high deposit – probably slightly above the scrap or recycling value of the battery. The effects on provisions and corresponding capital costs and risks for manufacturing companies and executive product responsibility organisations (PRO) must be assessed.
- It should be examined how a high level of customer acceptance for a deposit system can be established and how the system can be made as customer-friendly as possible. Among other things, the amount of the deposit, the necessary effort or user-friendliness, and the availability of information must be taken into account.
- The implementation and administration of a deposit system is comparatively inexpensive and proven. However, additional capital and warranty risks for those who place batteries on the market could be significant. At the same time, the deposit could provide the capital needed to build up the necessary dismantling and recycling infrastructure. The guarantee of capital risks by the public sector could be considered.
- Solutions for the appropriate calculation of the deposit and regulations for the passing on of the deposit when selling the electric car or the end-of-life (EoL) battery must be well-founded and carefully designed; otherwise, obstacles to the purchase of Battery Electric Vehicles (BEV) as well as transactions in used markets cannot be ruled out.
- Advantages could be that long-term customer loyalty is supported. The total cost of ownership (TCO) of vehicle batteries could be reduced by increasing the return quotas – and thus the recovery – of valuable materials.

The legislator should transfer findings (structural design, pricing) from use cases with high acceptance, especially those with a high deposit (e.g. rent deposits paid by tenants and not available during the rental period). One example from the automotive sector is CoremanNet for the management of used vehicle parts.[170] Even if a European solution is to be sought, a nation-state solution may be appropriate as a transitional

169 | See Hoyer 2015.
170 | See CoreManNEt.

solution in the event of a delay. According to experts, this is legally possible[171] and would have to be examined.

Like other policy interventions, such a deposit system should, of course, be regularly reviewed for its success and consequences and revised in the light of new experiences (e.g. in terms of the success of battery recycling as well as costs and benefits).

In sum, the Traction Batteries Working Group therefore recommends that a deposit for traction batteries and other incentive systems for ensuring maximum return quotas be examined.

- The **systemic potentials of traction batteries in the course of the energy turnaround** must be further investigated, taking into account the possibilities of digital technologies, and efforts must be made to realise them. Central points include:

  – **The use of simulations and big-data analyses to improve decision making** – for example, for predicting battery quantities for second-life applications for stationary power storage, determining existing and possible recycled components in traction batteries, and determining the circularity of the overall system;
  – **Integration of Circular Economy measures into relevant policy strategies** – in particular, national and European mobility, energy and hydrogen strategies;
  – **Assessment, further development, and commissioning** of possible implementation-oriented solutions of second life applications and vehicle-to-x.

These points must be shaped both at EU level and by the national legislator.

- In the long term, the **transfer of the above measures to the global context** must be achieved, in particular by:

  – Harmonisation with the regulatory system and networking with governments and other relevant actors from **third countries** outside the European Union and the European Economic Area (EEA) in order to increase the level of ambition globally and strive for a global balance (i.e. a level playing field);
  – Transfer of knowledge and cooperation within the framework of **international cooperation and development collaboration** in order to promote the Circular Economy in less developed economies (and ensure occupational safety and the environmentally safe handling of batteries in the case of leakage) as well as emerging markets for battery electric vehicles (BEV).

These points must be shaped both at EU level and by the national legislator.

5.2 Recommendations for action for business

- By collaboratively initiating **common (minimum) standards** and a systemic **design for circularity**, the industry can utilise synergetic potentials at different levels of action. Both individual actors (e.g. vehicle manufacturers, machine builders, and recyclers) as well as industrial associations and standardisation groups can become active here, in particular

  – at product level: This includes the modularisation of the traction battery, a circular design of the battery case, and a battery-friendly construction of the vehicles. The diversity of battery types, controls, and applications should be taken into account and, where appropriate, also harmonised.
  – at company level: increased use of the data in programmes for company management and administration – for example, battery data and cost assessment in the company's inventory management, runtime monitoring and malfunction monitoring (defect tracking) in customer relationship management, and problems and failure data to improve the service offering and basically as a basis for product improvements in the context of big data analyses.
  – at process level: This can be complemented by the modularisation of individual steps within process chains or recycling systems in order to be able to flexibly integrate technical innovations in the material composition of the battery as well as in plant engineering and value-added systems. The added value of existing industry 4.0 efforts (see, for example, the "administration shell"[172]) in this respect should be further explored.

171 | See Hoyer 2015.
172 | See Bundesministerium für Wirtschaft und Energie 2017.

– at system level: Embedding of products and processes in productive process chains and across the value chain, for example by developing new platform-based business models.

The aim should be:
1. **to extend the service life** of the first application;
2. to ensure efficient reuse in value-adding secondary applications (where appropriate);
3. to achieve high-quality recycling;
4. to promote innovation in the direction of automation.

- **Industry-wide agreements** are needed to specify **which operational and economic indicators** can be used to **measure circularity** and how these indicators relate to each other. In particular, agreements are to be reached on industrial cooperation and relevant specialist bodies:

  – **Distinguish between economic** (e.g. ROI on service business models), **environmental** (e.g. recovery rates), and **social** (e.g. jobs created) **metrics**, and **consider possible interactions.**
  – The **provision of the data required for this purpose** can benefit both external reporting and internal monitoring in terms of internal decision-making (for example, in the context of forecasting return volumes).
  – In this field, the **development of digital material and product passports** plays a central role. This can provide both static (material footprint, serial numbers, manufacturing information) and dynamic (respective owners, maintenance activities, condition (State of Health, SoH)) data efficiently, securely, and in a user-related manner over the service life of the batteries and the materials contained therein. The specific data must be defined in accordance with regulatory requirements, among other things.

- **The development and implementation of basic knowledge, (initial) education, and (technical) training** that will enable the scaling of the Circular Economy must be addressed in cooperation with politics and science. This includes:

  – Technical training, in particular to ensure occupational health and safety in the handling of end-of-life (EoL) batteries and the availability of trained personnel;
  – The further development and opening of training occupations (e.g. production technologist) for the Circular Economy;
  – The education of the population and specialist personnel on the basic principles of the Circular Economy (e.g. on resource conservation and climate protection as well as economic and business management qualifications).

- Economic actors should **provide relevant information and data** according to regulatory requirements **and promote collaborative exchanges** that support business models that enhance resource productivity.

  – This requires a positive-sum-game attitude and the identification of shared interests to incentivise the disclosure of useful information and the transparent exchange of information.

- It is the responsibility of industry to **further develop and scale up technologies and business models** that go beyond end-of-life (EoL) management of spent batteries and fundamentally increase the added value (costs and benefits) – not only of consistent closed-loop recycling but also of systemic productivity.

  – However, new business models such as leasing or sharing, require new ownership structures for the battery. These must be negotiated transparently in a dialogue with all actors. The effects on value allocation and liability must also be clarified.
  – By negotiating specific requirements and guidelines or etiquette for long-term cooperation between the actors, the incentive should be generated for all necessary actors.

- Strengthening **investment in the development, commercialisation, and scaling** of necessary technologies and infrastructure for the Circular Economy along all levers:

  – **Productivity increase and ecosystem**: Development of charging infrastructure and mobility systems to enable vehicle-to-x (V2X) as well as car- and ride-sharing for the maximum productive use of traction batteries during their first life.
  – **Return and dismantling**: widespread application of digital technologies to locate traction batteries at decision points (change of ownership), in particular end-of-life

(EoL), and expansion of necessary dismantling and logistics capacities.

- **Second life**: Establishment of technologies and capacities, in particular for the analysis of residual value, reprocessing, and recertification before placing on the market again.
- **Recycling**: The further development of recycling technologies with the aim of achieving optimum recovery rates across the entire process chain in high quality with optimised environmental impact and costs; scaling of capacities in Germany and throughout the EU.
- In this context, **public financing options, international capital markets, and cross-financing** through incentive systems (e.g. deposit systems) should be utilised and implemented, **taking into account recognised standards** (in particular the EU taxonomy for sustainable investments[173]) as well as further Circular Economy specific recommendations.[174]

- Economic actors – in particular vehicle manufacturers – should examine whether and how they can move towards planning and making business decisions across the entire value chain, **taking into account systemic resource and energy efficiency (entropy growth/residual exergy)**.

  - This should be implemented on the **basis of scientifically sound practices**. The aim should be to meet the requirements of the Circular Economy (see Section 5.3 Recommendations for action for the scientific community) in coordination with the public sector.

5.3 Recommendations for action for science

- By taking a **holistic view of economic and environmental target values** and **measurement methods**, science should establish a balanced basis for decisions to assess possible trade-offs and identify options for their solution.

  - This includes the **co-development and validation of operational/economic circularity indicators** in close cooperation with politics and business.
  - The basis for this is the **scientifically based contribution to generally accepted measurement parameters** – for example to determine the circularity, the carbon footprint, and the material and energy efficiency as well as other central consideration parameters (e.g. systemic energy efficiency and entropy/exergy as well as the differentiation between circularity, including production waste or post-consumer waste).
  - Through **proactive communication in politics, business, and civil society** and the **provision of methods and tools that can be applied without technical expertise** to assess systemic enthalpy and entropy (exergy), energy demand, emissions, material flows, and resource use as well as the success of Circular Economy business models, the scientific community helps to ensure knowledge transfer and support professional decision-making.

- Through **increased trans-disciplinary basic research**, the scientific community should promote the further development of Circular Economy-related technology and knowledge as well as the integration of these into innovative value chain systems, taking into account the economic and environmental effects of possible measures.

  - The Circular Economy should also be institutionally anchored in the colleges and universities by **establishing professorships/chairs.**
  - The **research infrastructure** should be developed in a targeted manner by the scientific community in dialogue with policy-makers in such a way that enables transdisciplinary research along the cycle.

- By integrating the Circular Economy into technical, scientific, and economic study courses, the aim was to **support** the development of sound **basic and applied knowledge of future actors in business, politics, and science**.

  - Integration of **lectures on the Circular Economy** in the relevant courses of study at colleges and universities;
  - Establishment of Circular Economy related **Master's programmes and in-depth studies;**
  - Development of **further training courses** for business;
  - Creation of **learning factories** for the Circular Economy; these can be integrated as realistic environments for professional training, teaching, and research.

- The scientific community can support the successful implementation of a Circular Economy at various levels through **application-oriented research and development** as well as the provision of appropriate training and further education.

173 | See Technical Expert Group on Sustainable Finance 2020.
174 | See European Investment Bank 2020.

- In particular, it should promote the **(further) development of technical, interdisciplinary solutions** for optimising the overall systemic effects (e.g. value chain representation, cradle-to-cradle assessment of effects of the Circular Economy), taking into account economic and environmental effects.
- For the use phase, technologies and methods that allow **the management of batteries for a long service and low ageing** and enable a sound decision to be made on a second life phase must be developed.
- At the level of the traction battery, this also includes the **design of battery systems suitable for dismantling** and the integration of these into the vehicle, the **introduction of new battery and production technologies, and the optimisation of material compositions**, particularly with regard to material purity, involvement in the (further) development of Designs for Circularity, and the development of models/test methods for the (more accurate) prediction of service life.
- At the process level, this is complemented by the **development of data platforms and standards,** in particular for the storage of data during the use phase, the development of automated **dismantling systems**, the provision of **tests regarding the second-life suitability of batteries**, the development of safe **discharge technologies,** the optimisation of existing **recycling processes**, and the development of new recycling processes and robust material synthesis processes for secondary raw materials. In all cases it is important to **consider the integration of effects on system and process chains.** In addition, methods with which the processes can be safely **scaled up to industrial scale** must be developed.
- At the material level, this includes the **further development of active and passive materials** in such a way that they can be **produced from secondary raw materials in a cost-effective manner** and that the materials themselves lead to low environmental pollution during their production and closed-loop recycling.

▪ Because of its neutral mediating function, science plays a central role, especially in the **development of modelling, simulation, and tools relevant for a Circular Economy**.

- In particular, this includes the **provision of practically applicable models and prognosis tools** for the estimation of physical material flows (dynamic and for defined system boundaries) and their thermodynamic assessment (exergy/entropy) and the life expectancy of batteries as well as the development of demand and decision optimisation in the field of second life and vehicle-to-x(V2X) – not least for the integration of the value chain for the provision of electrical energy and mobility (sector collaboration).
- **Digital twins** are to be built on the basis of validated models, and an associated (ideally web-based) **simulation platform** is to be developed (if necessary, together with industry). This will allow validated and robust predictions of material cycles as well as the associated environmental impacts and costs.
- New methods must be developed and validated for the **robust and valid measurement of, for example, recycling and energy efficiency**. These methods should be linked to the models and simulations in such a way that they can be reliably calibrated.
- On this basis, overall systemic market-oriented approaches to solutions are to be developed, and their step-by-step implementation is to be designed and ultimately supported.

▪ The further development of battery technology towards **solid state batteries** and other **new battery generations** (e.g. lithium sulphur batteries) must be sought and evaluated by science before heading in the direction of a Circular Economy. This includes the ability to recycle materials with high recycling rates and material purity and without loss of quality as well as the development of economical and environmental future-oriented processes.

6 Roadmap and outlook

The recommendations for action to politics, industry, and the scientific community described in detail in the previous chapter were prioritised by the members of the Traction Batteries Working Group and timed to achieve the outlined goal of a Circular Economy for traction batteries on the following roadmap.

In the short term – up to 2024 – the foundations must be laid for:

- making relevant decisions against a background of sound knowledge, appropriate models, and indicator systems;
- creating a level playing field through clear definitions of key concepts and the determination of rights and obligations;
- preparing investments;
- making the development of the next generation of traction batteries and their ecosystems compatible with the Circular Economy. The training of the next generation of professionals and decision-makers must be initiated right away. Already now, before the later EoL measures, systems and business models for the resource-productive production and use of traction batteries (e.g. ridesharing) must be created.

In the medium term, further **structures** that are robust for commercial, EU-wide scaling and create controlling-relevant transparency must be established in line with the rapidly expanding market for EoL traction batteries. The scaling up of technical, especially digital, options for the Circular Economy is necessary now at the latest (for example, with regard to digital product passports, digital twins, and machine learning). Significant investments are also required to achieve this. It is also necessary to adapt intellectual and business structures for the Circular Economy by creating models, tools, and new business models, in particular based on the Circular Economy (training) education developed in the early 2020s.

Based on this, the **breakthrough** to a Circular Economy can be achieved **by 2030:** As traction batteries are now starting to reach their EoL in large quantities, robust, scaled, and efficient Circular Economy systems – from collection to dismantling to efficient recycling[175] – are required. Measures relating to the multiple use of vehicle batteries in their first life in the vehicle - smart grid integration, sector coupling, and V2X – must also take effect now in order to ensure the cost-efficient generation of the necessary (charging) infrastructure. If the systemic potential of the Circular Economy for traction batteries is also taken into account in regulatory systems, economic, and scientific circles, important steps towards the Circular Economy in Germany have been taken.

175 | See Buchert et al. 2019.

Pilot projects ▶ **2021–2024: Short-term "lay the foundation"**

Public Policy

1. Definition of clear and mandatory **definitions and standards** (e.g. CO_2, human rights) while also maintaining data protection and security
2. Clarification of the **rights and duties** of all actors, for example in the matters of occupational health and safety, end-of-waste obligations, reporting, and the launch of **incentive systems** (e.g. deposit system for materials)
3. Establishment of a **central institutional** actor responsible for promoting the transformation
4. Ensuring **training and further education**

Business

5. Collaborative initiation of joint **(minimum) standards** for process chains and system design with the aim of establishing systemic designs for circularity
6. Establishment of **industry-wide agreements** for indicators, for example to **measure circularity** (economic, environmental, social and interactions thereof) as well as security-related aspects
7. Assurance that professionals are **trained** in EoL management for traction batteries

Science

8. Scientifically informed contribution to establishing generally accepted **key indicators, measuring quantities, and methods**
9. Technical and transdisciplinary **foundational research** focusing on supporting the optimisation of overall systemic effects
10. Provision of **academic training** for the circular economy

Pilot projects ▶ **By 2027: Medium-term "establish a structure"**

Public Policy

11. **Measures to increase transparency** in the industry and for their consumers and their technical implementation through Battery Passport and Data Spaces, such as standardised labelling to show environmental footprints
12. Scaling of **economic and scientific support** for relevant technologies, business models, and knowledge
13. **Harmonisation** of national and transnational regulations

Business

14. Provision of **relevant information** and data among relevant actors, for example by using **digital technologies** such as product passports
15. Development and scaling of **circular business models** that increase productivity beyond the recycling of old batteries
16. Scaling of investments for the circular economy, including **investment** in infrastructure for the collection and management of EoL batteries and digital technologies

Science

17. **Practical research and development,** particularly for new interdisciplinary solutions to optimise overall systemic effects

Pilot projects ▶ **By 2030: Long-term "breakthrough"**

Public Policy

18. Implementation of **sanctions** for failure to comply with existing requirements
19. **Consideration of the systemic potential** of traction batteries over the course of the energy turnaround (through simulations and big data analyses)
20. Application of measures to the **global context** for both main markets (race to the top) and developing economies (collaboration for development)

Business

21. **Planning that takes into consideration systemic resource and energy efficiency monitored throughout the value chain (entropy/exergy) as a measure of circularity**
22. Development of a Europe-wide infrastructure for the disassembly and recycling of traction batteries returning to the end of their life

Science

23. Provision of **methods and tools** for the assessment of energy and materials flows and their effects as well as business models, without the need for specialised technical knowledge

Figure 27: Roadmap for achieving the vision (Source: own representation)

6.1 Next steps

Open questions remain, and further cooperation is needed to clarify them. Civil society also plays a central role in some cases. In particular, the following points emerged in this context:

1. Prolong the service life of traction batteries
    a. Which data are absolutely necessary for the life cycle of the battery systems from the point of view of data protection and secrecy maxims?
    b. What commercial potential exists for automated battery replacement (battery swapping), and what effect could this have on the service life of traction batteries?

2. Close loops
    a. How should incentive and sanction mechanisms be designed in concrete terms in order to ensure optimal recirculation and high quality recycling of traction batteries?
    b. How can a thermodynamically based optimisation be broadly integrated into entrepreneurial activities?
    c. What potential do material substitutes (e.g. battery casings made of polymers instead of steel or non-toxic battery materials) have, and what effects could they have on the circularity of batteries?
    d. How can the German legislator design a Circular Economy for traction batteries and the necessary global value-added networks beyond its national borders?

3. Maximise systemic productivity
    a. How can the potential of traction batteries be used to optimise the electricity networks (sector coupling, vehicle-to-x – V2X)?
    b. What (active or controlling) role can users play?
    c. How can the negative effect of geopolitical tensions on sustainable development be reduced?
    d. How do vehicle-to-x (V2X) - and other multiple-use concepts such as car- and ride-sharing interact – for example, in terms of battery ageing, user comfort, and downtime?

Without the establishment of a circular model, the battery and thus electromobility will not be able to meet high expectations of today's society. There is a danger that certain groups will voice their reservations – with damaging consequences for the mobility and energy turnaround. On the other hand, the introduction of circularity will increase the economic and environmental benefits. This essentially involves the rapid construction of a product-services system integrated across the entire life cycle of the product, which stands not least as an example for other systems. With this report the members of the Traction Batteries Working Group of the *Circular Economy Initiative Deutschland* hope to have contributed to the transformation towards a Circular Economy for traction batteries. In many cases, like the sector as a whole, this is still in its infancy and will require further collaborative exchanges. It would now be the task of all the actors involved in politics, business, and science to resolutely proceed with implementing the recommendations for action outlined here.

Annex

A Glossary

The following terms are sorted by topic:

Term	Definition	Comment
Circular Economy	The Circular Economy aims to ensure the maximum value retention of raw materials used by adopting a system perspective – for example, through digital technologies, product redesign, and the reconfiguration of value chains. It thus emphasises the importance of higher resource productivity and ultimately the decoupling of value creation. It therefore consistently follows the waste hierarchy in which waste prevention comes first and incineration and landfill last. This is intended not least to avoid negative environmental effects (for example CO_2 emissions and ecotoxicity). It is particularly important to emphasise the distinction from the concept of "closed-loop recycling management" (Kreislaufwirtschaft) used in Germany, which has so far been more of a recycling-oriented waste management.[176] Circular Economy for traction batteries is defined in Chapter 1 of the General Report.	See CEID preliminary study[177]
(Resource) decoupling	Decoupling of economic performance and well-being from resource use and externalities. A distinction is made between relative and absolute decoupling. Relative decoupling takes place when economic growth outpaces the environmental and social consequences. Absolute decoupling occurs only when resource use and externalities decline as economic growth continues.	See International Resource Panel[178]
Critical raw materials	In accordance with the definition of the EU Commission: great economic importance with simultaneous high supply risk for the EU, see https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en	Even if not classified as critical, raw materials for traction batteries (e.g. nickel) can be of great importance for battery manufacture or on merit of their environmental impacts.
Important battery materials, substances, and components	For lithium-ion batteries, key metals, other substances, and materials for which physical closed-loop recycling is particularly important because of their footprint (carbon, water consumption, other environmental factors, human rights issues), criticality (according to the EU definition: great economic importance and high supply risk), and/or relatively high proportion of demand for batteries. A distinction must be made between the particularly important elementary metals/substances (e.g. lithium, cobalt, nickel, copper, and graphite), functional/engineered materials (e.g. cathode material), and components (e.g. electrodes, battery casings, or battery management systems).	
ACES	Autonomous, connected, electric, shared mobility: Umbrella term for the largest macro trends that promise to fundamentally transform the automotive industry through technological progress	
Car-sharing	Like ride-sharing but without the offer of a mobility service and simply the provision of a vehicle for individual users as needed. Although this will increase the mileage and possibly change the ownership structure, no increase in productivity of use (passenger kilometres per kilometre/kilowatt-hour) is to be expected.	Examples: Rental cars, sharing platforms such as "car2go"
Material or product passport (in particular: battery passport)	Digital tool for storing and providing information on the origin, durability, composition, reuse, repair, and dismantling possibilities of material (material passport) or of a product (product passport) as well as usage data/SoH and the location and handling at the end of the service life	See EU Commission Strategy for Data[179]

176 | See Sachverständigenrat für Umweltfragen 2020.
177 | See Weber/Stuchtey 2019.
178 | See International Resource Panel 2019.
179 | See Europäische Kommission 2020.

Term	Definition	Comment
Ride-sharing	Shared use of (electric) cars either from private vehicles (peer to peer) or in professionally operated fleets for mobility services. Because of the significantly higher utilisation (passenger kilometres per kilometre), the productivity of the vehicles used and the batteries they contain increases compared with individually owned vehicles. Ridesharing can also be an innovation driver because of the faster wear and tear in continuous operation. Through this and as a result of clearer ownership structures, this can support the easier implementation of Circular Economy strategies (design for circularity, durability, repair, and high quality recycling).	Examples: Carpools, shared taxis, (autonomous) buses, and trains
Smart grid integration (vehicle-to-grid V1G/ V2G or vehicle-to-X)	Controlled "smart" charging of electric vehicles (V1G) and bi-directional exchange of electricity between vehicle and grid (V2G) for the purpose of the lifetime optimisation of traction batteries as well as the systemic optimisation of charging infrastructure and energy availability. In order to continue to present all bidirectional charging options (e.g. direct exchange between vehicle and home storage without contact with the electricity grid), the term vehicle-to-X (V2X) is used as an alternative and extension to V2G. Various benefits can be expected from this, including additional revenue generation various network services (e.g. balancing power, frequency regulation), higher product utilisation (multiple use), and cost savings in network infrastructure expansion. Comment: The empirical evidence shows that the feared additional wear and tear of the traction battery caused by V2X does not have to occur in reality through targeted control; in fact, V2X can extend or even increase the service life of the battery under certain circumstances.[180]	This is not the focus of the working group but nevertheless an important prerequisite for market scaling. See GBA "Vision for a sustainable battery value chain by 2030" and IRENA "Innovation Outlook: Smart Charging"[181, 182]
Repurposing/Second life (SL))	Reuse of traction batteries or their components in new application contexts, mostly in less demanding applications after the end of the first "service life" (e.g. in scooters or freight vehicles) – but especially in stationary applications. If necessary after refurbishment as a whole battery or in individual modules. Continued use or reuse in the same application (passenger cars) is taken into account under "Repair or refurbishment"	In accordance with EU definition https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/1996-Sustainability-requirements-for-batteries
Reprocessing	Partly used as a synonym for recycling; however, in a narrower sense, it describes only the mechanical-physical steps of recycling (shredding/digestion and sorting/separation) based on physical properties. The output is usually various fractions/concentrates in which substances are enriched but which usually require further (metallurgical) purification steps in order to be used as a high-quality secondary raw material (see Figure 26).	
Closed-loop/open-loop recycling	Closed-loop recycling means the reuse of recyclates in the same application from which the input materials originate – for example, batteries are once again made from battery materials or metals. In open-loop recycling, on the other hand, the recyclates are also used in other applications – for example: nickel recycled from batteries is used in steel alloys.	Open-loop recycling allows a wider range of applications for the recyclates, thereby resulting in a larger market and possibly higher demand – but also the risk of higher quality losses in recycling. A closed loop in the sense of a 100% permanent closed-loop recycling of all materials is not physically possible, and an approach to this is also increasingly suboptimal from a thermodynamic point of view. This ideal is therefore not desirable.
Design for circularity	Comprehensive consideration of design for disassembly, remanufacturing, and recycling in product design	
Refurbishment	Lifetime extension of traction batteries at reduced power (e.g. remaining capacity, specific resistance) – for example, by replacing control elements or individual modules or by refurbishment (upgrades). The aim is to achieve a satisfactory operating condition of the used traction battery adapted to new vehicle applications. Afterwards use again as traction battery or in secondary use as in the case of the second life application	Sometimes the synonymous term "reconditioning" is also used - to distinguish it from reprocessing = remanufacturing as well as from repair (see glossary).
(Extractive) metallurgy	Smelting metallurgical (pyro/thermal) and/or wet chemical (= hydrometallurgical) processes for the disintegration and separation of ore concentrates, material composites, or material mixtures. For example, fine metals are achieved as output.	

180 | See Thompson 2018.
181 | See World Economic Forum 2019.
182 | See IRENA 2019.

Term	Definition	Comment
Recycling	End-of-life process for the material reuse of components, battery materials and/or substances through a combination of manual (dismantling), mechanical, thermal and/or metallurgical-chemical (pyro- and/or hydrometallurgical) processes. Defined here as the entire process – from the deactivation of the battery (components) to the completed extraction of raw materials (recyclates) ready for sale for the production of new battery materials – in a quality comparable to that of the primary material (i.e. usable for similar applications). A purely thermal recovery without recovery of reusable high-quality raw materials is not considered recycling because of the lack of physical cycle closure.[183]	Because of the high technical demands on functional materials (engineered materials), recycling according to this definition is generally possible only for metals (e.g. cobalt, nickel, copper, or lithium). The high-quality recovery of polymers or even graphite, if necessary, usually proves to be challenging or uneconomical.
Recycling rates = recovery rate (RR) = recycling quotas	Yields/recovery rates related to the overall battery recycling process. The RR describes the quotient of the mass of the physically reusable recyclate and the input mass into the overall recycling process. To be collected as the average over a financial year of an operational unit (recycling site or business unit). In addition to determining RR in relation to the total mass of the battery, differentiated RR for individual metals/substances (e.g. cobalt, lithium, nickel) are important. These refer to the sum of the metal/material contained in each battery, and only the recovered, actually reusable output may be counted for the RR. In multi-stage recycling processes, the losses of each individual stage must be taken into account (i.e. the total RR/yield is the product of the yields/efficiencies of each individual step).	Higher requirements are placed on recycling rates in terms of physical recycling management than on the current RR laid down in waste legislation. The latter usually do not refer to the reusable output streams of the overall process but rather mostly to input streams in the final process stage.
Repair	Lifetime extension of defective traction batteries by replacing control elements or individual defective battery modules or cells or by digital refurbishment (software upgrades). The aim is to restore the used traction battery to the same operating condition as before the defect.	Thus, repair is also a part of refurbishment, whereby the reuse is exclusively as a traction battery.
Responsible recycling	Analogous to responsible sourcing: Products are sent for high-quality recycling at the end of their life. There is full transparency on the EoL chain – from the collection of waste equipment to the different stages of the recycling chain to the output of the final recycling process. All processes along the chain meet defined technical, environmental, social, and ethical standards and can be audited and certified accordingly.	
Responsible sourcing	Provision of (battery) raw materials, taking into account internationally recognised standards regarding the protection of human rights and the environment. Noteworthy references in this regard are in particular the guidelines of the OECD[184] and the United Nations[185] as well as other relevant regulatory systems (e.g. the US and the EU).	Globally active companies and international corporate networks such as the Global Battery Alliance[186] are also active in this area.
Recyclate	Secondary raw material recovered through recycling (in particular purified active material or metals and substances contained therein, for example as metallic salts or in elemental form) of a quality comparable to that of primary raw materials. Can be used as input for the production of new products.	To be distinguished from intermediate products/intermediates from recycling processes that require further recycling processes before they can be used for new products (e.g. black mass)
Material purity/ recyclate purity	Purity of the recovered secondary raw materials with regard to contamination by other metals.	For the production of battery materials, the secondary raw materials should have the highest possible purity.
Recycling	In the sense of economic use; for batteries, this includes both refurbishment for reuse and recycling	Landfill or incineration is not considered to be recycling in the Circular Economy perspective.
Continued use, reuse	Ambiguous terminology used in practice; this includes the reuse of the battery (after upgrading, if necessary) in the same application as a traction battery (repair/refurbishment) or in a new application (second use/second life)	
Reprocessing = remanufacturing	Refurbishment to a "like new" condition combined with the guarantee that the traction battery or its components perform as good as or better than the original performance. In doing so, it must be taken into account how this state is to be defined for batteries (remaining state of health, SoH).	See "repair" and "refurbishment"

183 | See Sachverständigenrat für Umweltfragen 2020.
184 | See Organisation for Economic Co-operation and Development 2016.
185 | See United Nations Human Rights 2011.
186 | See World Economic Forum 2019.

B List of abbreviations

ACES	Autonomous, connected, electric, shared mobility
BEV	Battery electric vehicle
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
BMU	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety)
BMWi	Bundesministerium für Wirtschaft und Energie (Federal Ministry of Economics and Energy)
CAN	Controller area network
CE	Circular Economy
CEID	*Circular Economy Initiative Deutschland*
CEPS	Centre for European Policy Studies
EC	European Commission
RE	Renewable energies
EGD	European Green Deal
ELV	End-of-life vehicle
EoL	End-of-life
EoU	End-of-use
EPR	Extended producer responsibility
EU	European Union
FCEV	Fuel cell electric vehicle
GBA	Global Battery Alliance
HEV	Hybrid electric vehicle
IIOT	Industrial internet of things
IP	Intellectual property
CED	Cumulative energy demand
LCA	Life cycle assessment
LFP	Lithium-iron-phosphate
LIB	Lithium-ion batteries
LMO	Lithium-manganese-oxide
MaaS	Mobility as a service
Mio.	million
Bio.	billion
NCA	Nickel-cobalt-aluminium
NMC	Nickel-manganese-cobalt
PHEV	Plug-in hybrid electric vehicle
PRO	Product responsibility organisations
ROI	Return on investment
SL	Second life
SoH	State of health
TCO	Total cost of ownership
GHG	Greenhouse gas
V1G	Smart charging
V2G/V2X	Vehicle-to-grid/vehicle-to-x (bidirectional charging between the vehicle and the electricity grid (V2G) or home storage and other electricity consumers (V2X))

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F Background on the *Circular Economy Initiative Deutschland*

The *Circular Economy Initiative Deutschland (CEID)* was founded in 2019 with funding from the Federal Ministry of Education and Research (BMBF) to promote Germany's transformation to a Circular Economy in a multi-stakeholder approach. The overarching goal is to develop a roadmap for Germany towards a more circular, resource-productive economy by the beginning of 2021 and to derive recommendations for action for politics, industry, and the scientific community.

In a preliminary study published in July 2019, the office of the *Circular Economy Initiative Deutschland* derived 24 findings from the qualitative analysis of 12 European Circular Economy Roadmaps. From these, it was able to formulate 10 recommendations for German implementation.[187] The results of the preliminary study, validated by a comprehensive multi-stakeholder review, form the basis for the work of the *Circular Economy Initiative Deutschland* and are incorporated into the preparation of the final report, which will be published in 2021.

Supported by members from business, science, civil society, and politics, the *Circular Economy Initiative Deutschland* offers a broad stakeholder dialogue in order to develop a systemic approach to address key challenges for the Circular Economy.

The work of the *Circular Economy Initiative Deutschland* is structured in three working groups (see Figure 28):

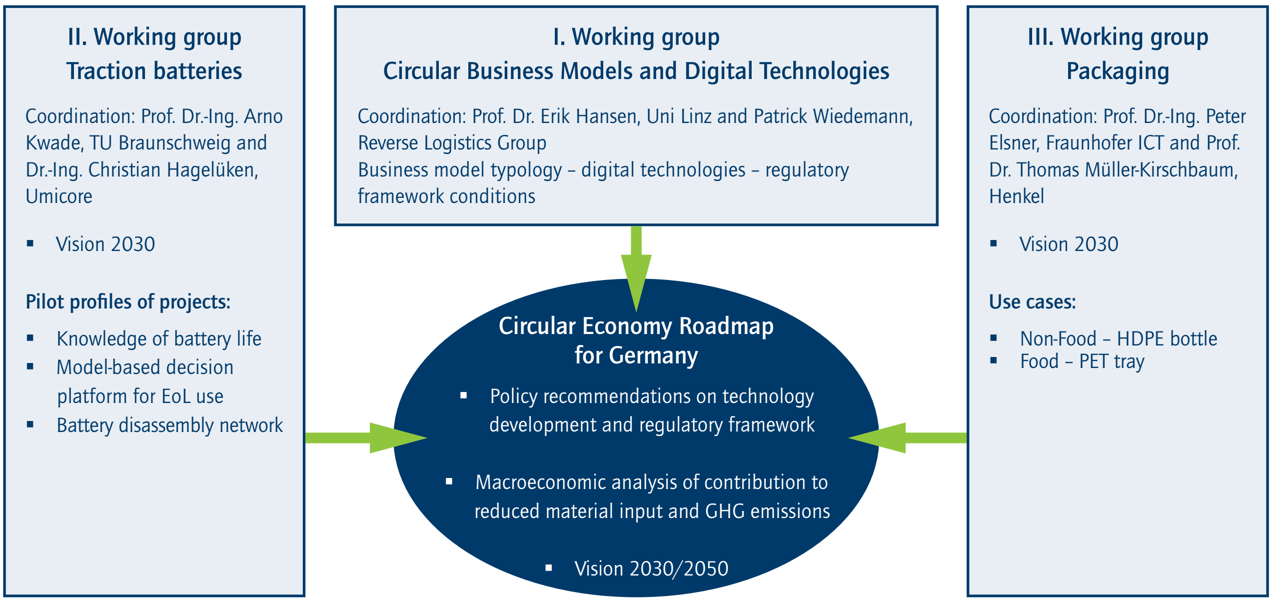

Figure 28: Presentation of the Circular Economy Initiative Deutschland and the three working groups (Source: own representation)

187 | See Weber/Stuchtey 2019.

- At the conceptual level, the Business Models Work Group deals with the potentials of circular business models and digital technologies as drivers of innovation.
- The Packaging and Traction Batteries Work Groups work along their respective sector-specific functional systems. The content of the work in the working groups is based on a holistic life cycle approach (product development, production, use, and reuse).
- The working and steering committee of the *Circular Economy Initiative Deutschland* is made up of members from science, business, and civil society as well as the Federal Ministry of Education and Research (BMBF), the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU), and the Federal Ministry for Economics and Energy (BMWi). This guarantees close coordination between the members and the office of the *Circular Economy Initiative Deutschland* and ensures permanent connectivity with German politics.
- The office of the *Circular Economy Initiative Deutschland* coordinates the entire process and develops the Circular Economy Roadmap Deutschland.

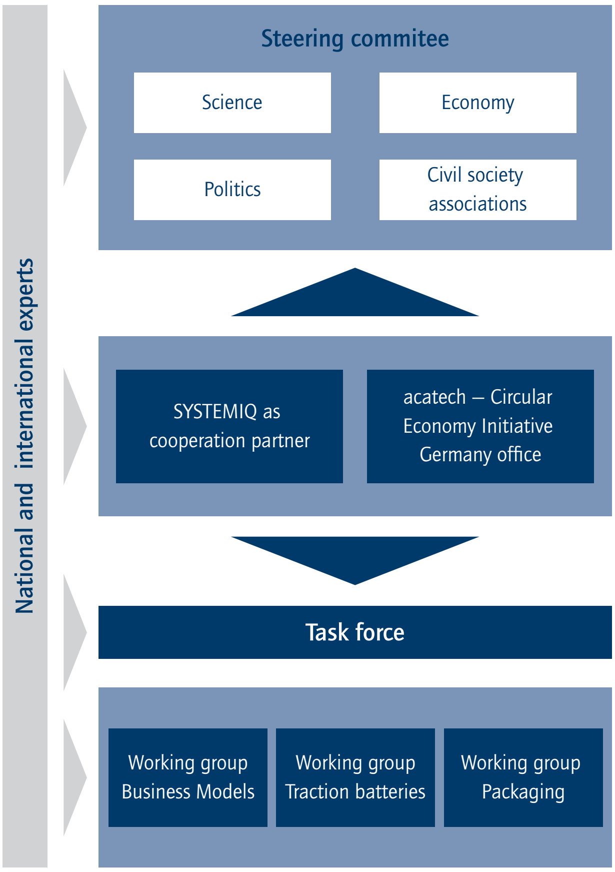

Figure 29: Organisational chart and focus of the Circular Economy Initiative Deutschland (Source: own representation)

The choice of the topic of traction batteries for the *Circular Economy Initiative Deutschland* was obvious for several reasons:

1. Because of the central role of the battery in the value creation and technical market leadership of electric vehicles (BEV), the relevance of this sector for Germany as a business location is significant. The comprehensive management of this central value chain represents an opportunity to provide an alternative to the declining value added from the "old" industry – in terms of jobs, investment opportunities, and sales potential.

2. However, because of the high market dynamics (e.g. as a result of high investment costs as well as the emergence of new centres of global industrial competence), it is important to realistically compare the risks and opportunities of circular battery value chain. Finally, the rapid global growth[188, 189] of (battery) electric mobility must be made sustainable because the environmental footprint of a battery (cradle-to-gate) is essential for its contribution to the decarbonisation of the mobility sector.[190]

3. However, in order to ensure social acceptance and to protect people and the environment elsewhere in the world when it comes to the production, use, and recycling of batteries, systemic action is required now. This is because establishing an adequate recovery and recycling infrastructure for the increasingly larger quantities of used batteries requires sufficient lead time and because the new batteries should also be used as long and productively as possible, especially during the steep market growth over the coming decades. It is also recommended that the batteries be designed to be easy to dismantle, maintain, and recycle.

4. From the perspective of the Circular Economy, the battery system is also a key issue in order to be able to learn lessons for building circular value creation systems. The system provides a clearly definable analysis framework with clearly definable material flows. The case study of the battery system also has conflicts of interest that can be clarified only in the context of a holistic approach (see Section 3.4 in the general report) and

188 | See International Energy Agency 2019.
189 | Forecasts predict that the market for battery electric vehicles (BEV) will grow rapidly by 20–40% per year in 2030.
190 | See World Economic Forum 2019.

which can therefore particularly benefit from the multi-stakeholder format of the *Circular Economy Initiative Deutschland*. The Circular Economy in batteries has a signal effect: Electromobility and traction batteries are a new application with a high impact on resources. Here, it is essential to think about the Circular Economy from the very beginning. The Circular Economy for traction batteries could even be a reference example for other new resource-relevant technologies.

5. Although the material flows and the direct greenhouse gas (GHG) saving potential of the battery sector are relatively low in the overall economic context, the relevance of the closed-loop recycling management for traction batteries is high: from maintaining the value of the partly critical materials contained in them to productivity gains through maximised use (shared mobility, vehicle-to-grid) to improved supply security for critical raw materials and the life cycle assessment of electromobility and systemic leverage effects for the energy turnaround.

G Background and methodology of the Traction Batteries Working Group

The work of the Traction Batteries Working Group benefited from the extensive participation of high-profile participants from business, science, and civil society (see Figure 30 below). It consists of key stakeholders, whose expertise covers the entire value chain of traction batteries: The participants include refiners of base materials, tool manufacturers, and battery producers as well as logistics companies, service providers, and recovery and recycling companies.

- Top-class representatives from science and civil society or members of platforms provide sound expertise and perspectives outside the business community.
- The participation of the Federal Ministry of Education and Research (BMBF), the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU), and the Federal Ministry of Economics and Energy (BMWi) in the steering committee ensures the link with the political world. The participation of relevant corporate platforms (Competence Network Lithium-Ion Batteries - KLiB, World Wide Fund for Nature - WWF, World Economic Forum - WEF) supports the connection to civil society and relevant corporate networks.
- The office of the *Circular Economy Initiative Deutschland* is responsible for process coordination and provides content-related support. It also ensures the connection to other national and international initiatives, such as the National Platform Mobility (NPM), the European Battery Alliance (EBA250), and the Global Battery Alliance (GBA) as well as relevant activities of the European Commission.

Methodology

The present *final report of the* Traction Batteries Work Group within the framework of the *Circular Economy Initiative Deutschland* is the coordinated result of a ten-month multi-stakeholder process with actors from business, science, and civil society (see overview of participants in the chapter Project in the General Report). In accordance with the general objectives and cartel law provisions of the *Circular Economy Initiative Deutschland*, the cooperation

Coordination

Industry: Dr.-Ing. Christian Hagelüken – Umicore, Director EU Government Affairs

Sciences: Prof. Dr.-Ing. Arno Kwade – TU Braunschweig, Director Institute for Particle Technology, Spokesperson of the Board, LabFactory

Current members

Industry

ACCUMOTIVE, BMW, covestro, DAIMLER, interseroh, PEM MOTION, RLG, SAP, SIEMENS, TRUMPF, umicore

Sciences

Fraunhofer IPK, HZDR, KIT, Öko-Institut e.V., RWTH Aachen University, TU Berlin, Technische Universität Braunschweig, TU Clausthal

Civil society, platforms and networks

Agora Verkehrswende, GRS Batterien Gemeinsames Rücknahme System, KLiB, NPM Nationale Plattform Zukunft der Mobilität

Figure 30: Participants of the Traction Batteries Working Group (Source: own representation)

between the actors involved within the working group was limited exclusively to the pre-competitive area. Six working group meetings, which were planned and carried out by the office of the *Circular Economy Initiative Deutschland* together with the working group leadership and spread out over the entire period, represented the central coordination mechanism. In concrete terms, the meetings offered the working group members the opportunity to discuss and decide together on thematic priorities and substantive positioning. Intensive preparation and follow-up of the working group meetings as well as iterative coordination loops between the individual meetings ensured a high degree of stakeholder involvement in the development of the topics and the positioning of the content.

The results of the final report summarise the discussions and common positions of the working group. In addition to these internal coordination loops, an external review of individual chapters was carried out by renowned experts from the scientific community.

Based on the identification of topics of particular importance for the concrete implementation of a circular battery value chain in Germany, three project groups were formed from within the working group. Each of these drafted a pilot profile in parallel to the working process of the group as a whole (see Chapter 4, Pilot Topics in the General Report, and Annex I, Pilot Profiles I, II, and III). This parallel working process was also structured by regular virtual meetings of the project groups. These were organised and carried out by the office and the respective moderators of the pilot projects. The results of the profiles are based on the input of the respective project groups. The content and central statements of the individual profiles were also coordinated with the traction battery working group in regular consultation loops. Finally, each pilot profile was subjected to external review by selected experts from the scientific community.

H Material flow analysis of Circular Economy measures until 2050

A material flow analysis by the Wuppertal Institute[191] commissioned by the SUN Institute Environment & Sustainability quantifies possible effects of Circular Economy measures on the economy – in terms of material flows, energy consumption, and CO_2 effects as well as economic parameters until the year 2050.

The optimised recovery of raw materials from the **batteries of electric vehicles** was chosen as the first focus topic – in view of the relevance for a transformation to a recycling management as outlined in the report of the working group. To this end, various scenarios were developed in consultation with the experts of the working group. The basic assumptions and results of these are presented below. In concrete terms, the following aspects were taken into account:

- Assumptions on the ramp-up of the electric vehicle stock until 2050
- Assumptions on the useful life of the batteries
- Assumptions on the battery technology used and the resulting raw material requirements
- Assumptions on the quota of exported vehicles
- Assumptions on continued use/second life
- Assumptions on achievable recovery quotas
- Assumptions on the reduction of cumulative energy consumption through optimised recycling

Assumptions on the ramp-up of the electric vehicle stock until 2050

Developing a stock of Battery Electric Vehicles (BEV) is crucial for the amount of raw materials available for recycling. According to the German Federal Motor Vehicle Office, only 136,617 battery-powered passenger cars were registered in Germany in 2020.[192] The German government would like these figures to be massively increased in the coming years[193] and driven by a global mega-trend.[194]

For the development of the stock, a scenario from BCG/Prognos[195] was used here. This assumes a stock of 8.9 million battery electric vehicles in 2030 (assuming strong financial incentives for the further expansion of electric mobility and the simultaneous shift of transport services (e.g. to local public transport[196])). For the period up to the year 2050, an exponential increase in the number of new registrations per year was assumed.[197] This would lead to a stock of 25.7 million electrically powered vehicles in 2050, which is in line with other estimates (e.g. the range of scenarios developed by the Oeko-Institut for the Federal Environment Ministry as part of the project "eMobil - 2050 scenarios for the possible contribution of electric transport to long-term climate protection"[198]).

Assumptions on the useful life of the batteries

The vehicles (and batteries) contained in this stock will become end-of-life vehicles after a certain period of use and should then be sent for high-quality recycling. An average value of 12 years was assumed for the duration of this service life. This includes a further improvement in the durability of the batteries during the period under review as well as intensified efforts to repair them during the service life.

An average useful life of 12 years includes both a certain proportion of batteries that fail early in the use phase as well as a certain proportion of batteries that are used for significantly longer than 12 years. For the distribution of the failures, a Weibull distribution with the core parameters k (form of distribution) = 4 and T (average service life) = 12 was chosen based on literature references.[199]

Assumptions on the battery technology used and the resulting raw material requirements

The possible contributions to climate and resource protection through optimised recycling of batteries from electric vehicles depend on the quantity of raw materials contained in them – and thus on the battery technologies used.

191 | See Wuppertal Institute [forthcoming].
192 | Battery Electric and Hybrid/FCEV as of 1 January 2019.| See Kraftfahrt-Bundesamt 2019a.
193 | See Bundesministerium für Wirtschaft und Technologie et al. 2011.
194 | See International Energy Agency 2019.
195 | See Boston Consulting Group/Prognos 2019.
196 | See ebd.
197 | Starting from the target values for 2030 and 2050, an even distribution of stock growth has been assumed for the intermediate steps here for the purpose of simplification.
198 | See Öko-Institut 2014.
199 | See Sander et al. 2017a.

Within the framework of this scenario development, the results of the Fab4Lib project, which is funded by the German Federal Ministry of Education and Research (BMBF), will be used for this purpose. The project aims to research innovative solutions along the value chain of lithium-ion technology and validate them in demonstrators.[200]

The following Table 3 shows the assumptions developed there for the development of the battery technologies used: "According to current knowledge, storage technology in the field of electric vehicles is clearly dominated by different variants of lithium-ion cells. This can be considered very likely at least until 2030. The medium-term developments up to 2030 are therefore much more certain than the long-term view up to 2050. Technological innovations that could have a disruptive effect on the market (e.g. solid state batteries) were not taken into account in the considerations" In view of the dynamic developments in battery technologies, it was assumed here on the basis of discussions in the modelling working group that 90:5:5 batteries will not come onto the market before 2040 and thus, because of the service life of traction batteries in the period under consideration, will not be available in significant quantities for recycling.

Based on these assumptions, the next step is to estimate the quantities of the raw materials nickel, cobalt, and lithium (which are the focus of attention here) contained in these batteries and which would potentially be available for recycling. The following table shows the assumptions chosen here for the average quantities of the relevant metals per battery unit in a vehicle based on the data given in Fab4Lib for the average capacities of the individual battery types.[201]

	Battery type	Proportion of the battery types on sale		
		2016	2030	2050
	NMC (1:1:1)	32%	–	–
	NMC (5:3:2)	4%	–	–
	NMC (6:2:2)	–	45%	–
BEV	NMC (8:1:1)	–	45%	54%
	NMC (90:5:5)	–	–	36%
	NCA	16%	10%	10%
	LMO	12%	–	–
	LFP	36%	–	–

NMC = Nickel–manganese–cobalt
NCA = Nickel-cobalt–aluminium
LMO = Lithium–manganese–oxide
LFP = Lithium–iron–phosphate

Table 3: Assumptions on the types of batteries used until 2050 (Source: Buchert et al. 2019)

Battery	Mass of metals in the cells, in kg	Of which lithium (kg)	Of which nickel (kg)	Of which cobalt (kg)
LMO	69.9	2.7	0	0
LFP	37.8	1.6	0	0
NMC (111)	87.5	6.5	17.5	17.5
NMC (532)	82	6	25	10
NMC (622)	75	5.5	27	9
NMC (442)	69.5	5	17	8.5
NMC (811)	66	5	32	4
NCA	116.8	8.8	56.8	10.4
NCA+	127.2	9.6	69.6	4

NMC = Nickel–manganese–cobalt
NCA = Nnickel-cobalt–aluminium
LMO = Lithium–manganese–oxide
LFP = Lithium–iron–phosphate

Table 4: Metal contents of different lithium-ion batteries (Source: own calculations based on Fab4Lib and BloombergNEF)

While the further development of battery technology for the use of these raw materials will lead to significant changes – significantly less cobalt per battery unit but significantly more nickel – constant input quantities were assumed for the other components (e.g. electronics, housing). For this purpose, the life cycle assessment for the "Recycling of Lithium-Ion Batteries" (LithoRec) of Buchert et al. was used. [202]

200 | See Elektroauto-News 2018.
201 | Lithium iron phosphate (LFP) = 20 kilowatts per hour; lithium manganese oxide (LMO) = 30 kilowatts per hour; nickel cobalt aluminum (NCA) = 80 kilowatts per hour, and nickel manganese cobalt (NMC) = 50 kilowatts per hour.
202 | See Öko-Institut 2011.

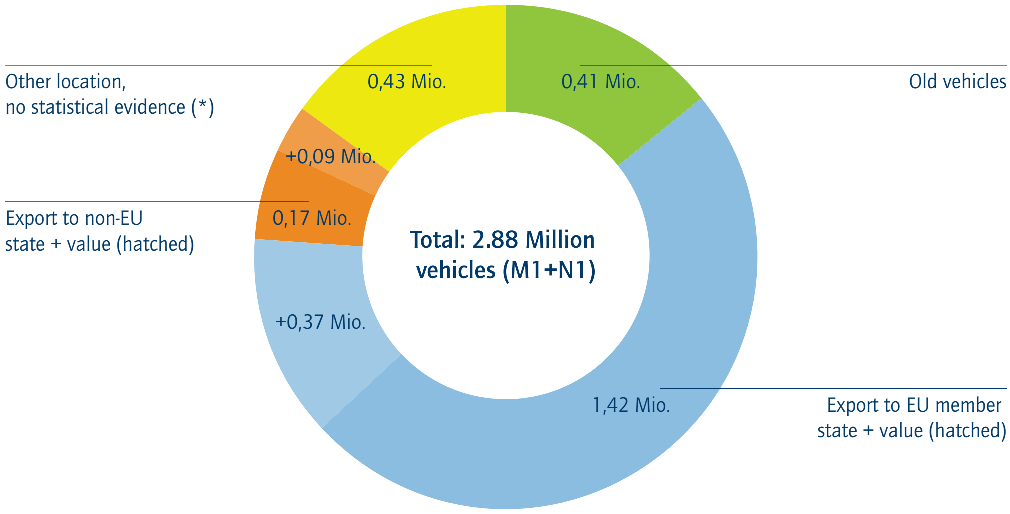

Figure 31: Whereabouts of deregistered vehicles in Germany (Source: Umweltbundesamt 2016)

Assumptions on the quota of exported vehicles

The vast majority of the vehicles permanently taken out of service in Germany were exported as used vehicles.[203] Analyses commissioned by the Federal Environment Ministry on the whereabouts of end-of-life vehicles have shown that a relatively small proportion is shipped directly from Germany outside the European Union. However, a larger proportion often ends up in Eastern European EU member states after a second use phase.[204]

At this time, it is not foreseeable whether similar usage structures will develop for electric vehicles. The comparatively high acquisition costs for electric vehicles could support such trends. At the same time, the requirements for a charging infrastructure or the development of new leasing business models expected in terms of the value, criticality, and environmental footprint of the materials used could lead to an increased number of such vehicles remaining in the European Union.

For the purpose of considering high quality and environmentally friendly recycling, this study considers only exports outside Europe as such; recycling in other EU member states is considered domestic.

Against this background, two alternative options were assumed for the calculations:

- Option 1: Export quota 10%
- Option 2: Export quota 50%

These are net export quotas because, to a small extent, electric vehicles could also be imported into the European Union for recycling. At the same time, it can be assumed that these vehicles will also be recycled abroad – but not to a quality standard comparable to that in Germany or the EU (because of the lack of legal requirements). It is therefore assumed that half of the recovery rates possible in Germany and the EU are also recovered for exported vehicles.

Assumptions on continued use/second life

Lithium-ion batteries can typically be used in battery-powered vehicles until their performance and storage capacity has dropped to around 80%.[205] However, even with such reduced performance, there are many other applications for which these batteries could be used in a second phase of use, thus saving the production of a new battery for these purposes:

203 | See Umweltbundesamt 2019.
204 | See Sander et al. 2017b.
205 | See Bobba et al. 2019.

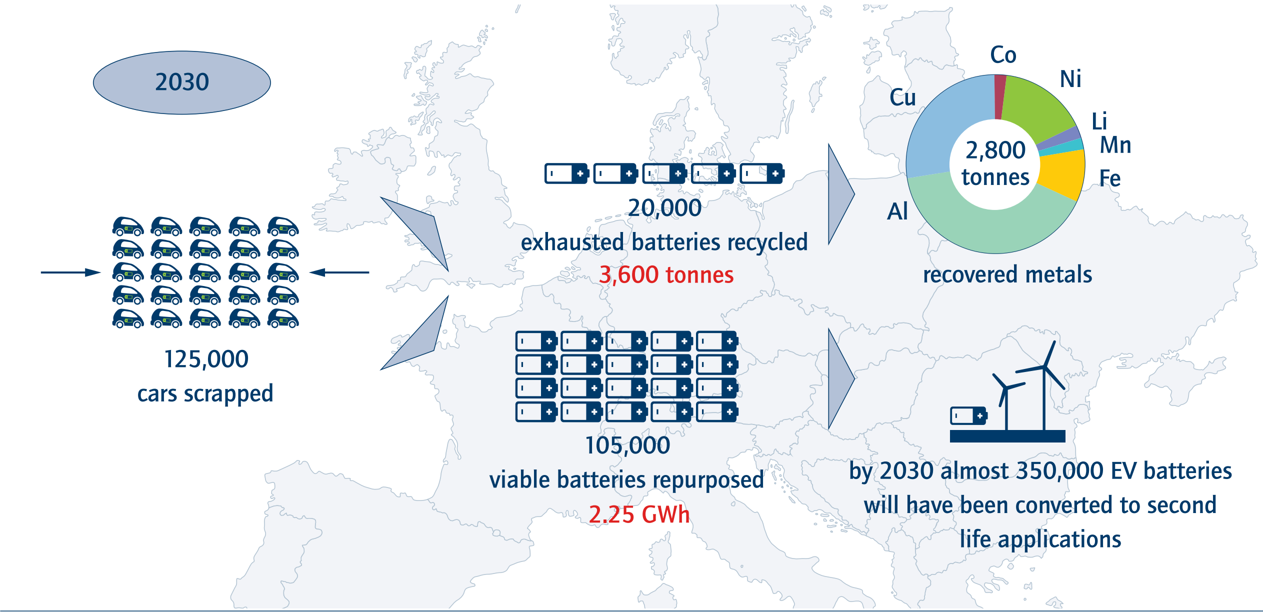

Figure 32: Scenario with extremely high proportion of batteries in a second life (Source: elementenergy 2019)

"...thus, not surprisingly, there is a high interest and potential for less energy-demanding applications, e.g. residential buildings, uninterruptible power supply, sweepers and driverless transport vehicles.[206, 207, 208, 209]

At present, it is hardly possible to reliably estimate the proportion of lithium-ion batteries that will actually be used in such secondary applications. In the literature, extremely different statements are made. These range from 85% (ElementEnergy,[210] see Figure 32) to estimates that the demand for second life is restricted to a limited number of technically comprehensive qualified storage applications. Studies on market relevance point out, among other things, that estimates for second life applications are subject to uncertainties regarding actual demand[211] "(...) there is a risk that such applications are obsolete at the time when the volumes of available used EV batteries become large" (see the in-depth study on second life in the general report).

Against this background, different scenarios are to be considered, which, based on Bobba et al. 2019, assume 0%, 20%, and 50% second life.[212] For this purpose, the assumptions were made that

- the batteries remain in this second use phase for 8 years,
- the batteries continue to decrease in their performance so that on average, a capacity of 60% of a new battery is assumed[213]
- third, because of the decentralised distribution in a wide range of applications, a final recollection rate for subsequent recycling of 80% can be assumed. This recollection rate will largely depend on actual use (for example, in private households or industrial applications) as well as on general conditions such as the possible introduction of a deposit on lithium-ion batteries.

With these assumptions, the options 20% and 50% second life delay the point in time when the raw materials contained in these

206 | See Bobba et al. 2018.
207 | See Rehme et al. 2016.
208 | See Rohr et al. 2017.
209 | See Bobba et al. 2019 , S. 280.
210 | See elementenergy 2019.
211 | See Kurdve et al. 2019.
212 | Bobba et al. 2019 even consider a Second-Use rate of 70% in their scenarios; however, this was not considered realistic from the point of view of the members of the working group.
213 | For the sake of simplicity, the substitution of a nickel-manganese-cobalt (NMC) battery was assumed. In practice, of course, other types of batteries (e.g. lithium iron phosphate (LFP) batteries) would also be replaced.

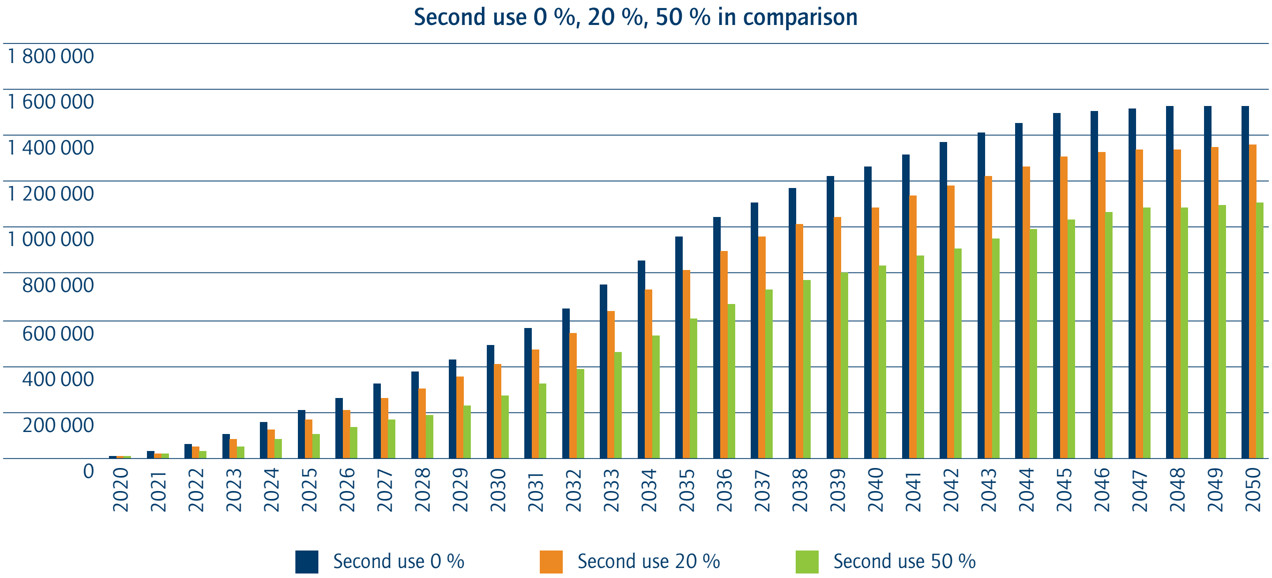

Figure 33: Annual amount of spent vehicle batteries from 2020 to 2050 for a second use of 0%, 20% and 50% (Source: Wuppertal Institute)

batteries are available for recycling (see Figure 33). If 50% of the batteries were to be recycled into a second life, for example, the first year with a quantity of more than half a million batteries for recycling would be delayed by 4 years (from 2030 to 2034). At the same time, the batteries used in second life would continue to generate added value during this period, for example in the energy sector by providing network services. Even with a second-life rate of 50%, only an additional 16% of market demand for key battery materials could be covered in 2030 given the strong market growth. In this scenario, almost 750,000 batteries would still be put to second life use in 2050 alone; these could then be successively recycled in the years after 2050.

In this scenario, the reuse of traction batteries in secondary use reduces the need for new batteries, the production of which would cause a considerable net carbon/material footprint (even assuming later availability for recycling and thus possible credits). For the savings achieved by extending the useful life of the batteries in a second phase of use, the results of Melin[214] were used. In the context of a review of existing life cycle assessments, these suggest the range of estimates of cumulative energy demand (CED) per battery.[215] Based on the data of Peters et al. 2017[216] and in consultation with the experts of the working group, a CED of 1,200 megajoules per kilowatt-hour of capacity was assumed.[217]

Refurbishment

In addition to the use of batteries for other purposes, an even more obvious approach in the sense of the inner rings of a recycling management is the extended service life of batteries for their original purpose through refurbishment. This lever comes into action before the battery loses so much capacity that it can no longer be used for its intended purpose.

Analogous to the future market relevance of second life, the literature also contains very different assessments on the topic of refurbishment – both with regard to market relevance and the associated savings effects. For example, Kampker et al.[218] have estimated the economic and environmental effects of remanufacturing batteries from Battery Electric Vehicles (BEV) and calculated a reduction of the Cumulative Energy Expenditure (CED) per kilowatt hour of battery capacity of 224.1 megajoules – this would correspond to a theoretical reduction in energy demand of about 20% compared with the assumptions used here for the

214 | See Melin 2019b.
215 | "In some of the most referred reviews of previous literature the cumulative energy demand for battery productions are within ranges such as 500 MJ/kWh–2000 MJ/kWh (average 1030), 316 MJ/kWh–2,318 MJ/kWh (most likely 960), 349 MJ/kWh–651 MJ/kWh and 2.4 MJ/kWh–1062 MJ/kWh | See Melin 2019a, S.3.
216 | See Peters et al. 2017.
217 | For the estimation of CO_2 emissions, the current electricity mix in Germany (2019) was initially assumed here; See Federal Environment Agency 2020.
218 | See Kampker et al. 2016.

primary production of a battery. Under other assumptions about the further life of the batteries after the refurbishment Richa et al. come to 49% savings of the CED.[219] In addition, a life cycle assessment (LCA) carried out as part of the LiBRi research project shows that savings of 95% in greenhouse gas emissions can be achieved with a cell exchange of only 5%.[220] Against the background of the range of these figures, a saving of 80% of the cumulative energy expenditure (CED) per battery through repair measures was assumed for the further calculations. The batteries are then reused in the original vehicles.

According to Kampker et al.,[221] there is also significant cost-saving potential; this was estimated at € 40 per kilowatt hour compared with a new battery using the lithium-ion battery of a Chevrolet Volt as an example. With increasing economies of scale, these savings could be increased to up to € 60 per kilowatt hour; this would correspond to a saving of one third compared with a new battery. Extremely dynamic price developments have been observed in recent years – both in battery production and in the remanufacturing process: For battery costs, the Joint Research Centre of the European Union (JRC) had assumed costs of € 215 per kilowatt hour as late as 2017;[222]current forecasts by Bloomberg New Energy Finance (BNEF) for 2030 assume around € 55 per kilowatt hour.[223]

If, from 2030 onwards, 25% of the batteries reaching the end of their useful life (assumption: export 10%, 0% second life) were to be refurbished, assuming an average price of € 55 per kilowatt hour and a constant savings potential of 33% of the costs of a primary battery, this would result in savings of around € 5.3 billion and 282 petajoules of energy requirement.

Assumptions on achievable recovery quotas

In order to produce secondary raw materials, the metals contained in batteries must be recovered at the end of their useful life through recycling processes. The actual recovery quota for individual raw materials from the batteries is decisive here and not, for example, the recovery rate under waste legislation. Although this is based on the entire vehicle, it is measured by the proportions that are recycled and not by the proportions of the various raw materials that can be recycled and reused in the end.

From such a systemic perspective, two successive processes must be distinguished for the recovery of metals from batteries:

- In the first step, the batteries must be disassembled into their individual parts – usually by shredding; alternative processes are currently being developed.
- In the second step, the processed metals are subjected to various hydro- or pyrometallurgical processes. The system boundaries of the recycling process are presented in the general report of the working group.

In view of the numerous activities in the field of research and development on the recycling of batteries,[224] a wide range of information can be found on the proportions of raw materials (e.g. lithium, cobalt, and nickel) that could be recovered in an optimised recycling system. The traction batteries working group has developed the following table, which provides an overview of the recovery rates to be aimed for. It is based on technical expertise from industry, science, and academic research. These represent commercially actionable values – taking into account the entire recycling process and the high-quality recovery of the combination of materials mentioned.

On the basis of these assumptions regarding the material content per battery, the quantity of batteries that fail and the total recovery rates, the total quantity of raw materials that can be recovered between 2020 and 2050 was determined for each of the scenario variants (export rate 10% and 50%; second life 0%, 20%, and 50%).

Material	Recommended recovery rates 2030
Lithium	85%
Cobalt	90%
Nickel	90%
Copper	90%
Steel	95%

Table 5: Optimised recovery rates for raw materials from traction batteries (Source: own representation)

219 | See Richa et al. 2017b.
220 | See Daimler AG 2014.
221 | See Kampker et al. 2016.
222 | See Lebedeva et al. 2018.
223 | or USD 62 in constant 2018 prices.| See Goldie-Scot 2019.
224 | See Melin 2019b.

Assumptions on the reduction of cumulative energy consumption (CED) through optimised recycling

Recycling processes can be optimised with a view to a large number of different targets (e.g. costs, environmental emissions, or energy consumption).[225] The focus of the observations made here is on the contributions of a recycling management to climate and resource protection. For this reason, the reductions in cumulative energy consumption as an indicator of the necessary energy input are assessed below.

Two different aspects must be taken into account:

1. The recovery of raw materials such as lithium, cobalt, and nickel as well as the other materials they contain leads to savings in resource consumption as well as associated social and environmental effects such as greenhouse gas emissions. This is because it can replace the production of new raw materials.
2. At the same time, the recycling processes required for this purpose also involve resource and energy consumption; these must be taken into account when calculating net savings.

On 1) to determine the concrete savings from lithium, cobalt, and nickel, the ecoinvent 3.6 database[226] was used; this provides data for the necessary primary production. Here it must be taken into account that these values can, of course, only ever represent an average process – from which actual processes can deviate significantly. For the credits of the other materials from the battery and module disassembly, the results of Buchert et al. 2019[227] were used. Here, it was assumed that a recovery of battery quality would be achieved so that primary material could be saved to the same extent.

On 2) For the necessary expenditures for the pyrometallurgical recovery process, the process description from ecoinvent 3.6[228] was used analogously. Here, it is stated as 20.02 megajoules per kilogram of battery. Here, too, it should be taken into account that the values for specific systems with their technical advancements could have different values in individual cases.[229]

225 | See Worrell/Reuter 2014.
226 | See Wernet et al. 2016.
227 | See Buchert et al. 2019.
228 | See Wernet et al. 2016.
229 | The process documented here (also in the latest version of ecoinvent) uses data from the year 2007, which, of course, cannot exactly map the process in 2020 nor in 2050. In this respect, the most recent, publicly available data was used here for the purpose of simplification.

I Pilot profile

Pilot Profile I: "Understanding the service life of the battery"

1 Motivation and objective

Pilot profile I "Understanding the service life of the battery" is an in-depth supplement to Section 4.1 in the general report and describes concrete recommendations for action. Their implementation will become much more important with the planned increase in electric mobility in Germany because the increasing production of lithium-ion batteries is associated with negative influences on the environment as well as increasing dependency on resources.

These influences and dependencies can be decoupled or reduced through a stronger closed-loop recycling of production- and environmentally-intensive materials in the sense of the Circular Economy. The use of data and information from the battery life cycles plays a central role in the economic implementation of the associated cross-company and supply chain cooperation as well as an economical, environmental, and efficient regulation of the closed-loop recycling. Incentives and uniform standards for their provision must be created by the relevant actors. The *Industrial Data Spaces* and *Product Passports* activities funded by the German Federal Ministry of Education and Research (BMBF) offer valuable preliminary work in this area.

This pilot profile defines the framework for a cross-company information platform to promote the closed-loop recycling of lithium-ion batteries in order to enable further working groups, research projects, and implementation planning based on this.

1.1 Current challenges in the system

A Lack of data complicates the closed-loop recycling and assessment of the effects

i Economic-environmental assessment
There is currently insufficient information on material and product properties of lithium-ion batteries as well as on the contributions of second life and recycling. A robust life cycle assessment is therefore rather time-consuming. The lack of confidence in the environmental compatibility of these batteries is becoming a challenge for the electrification of individual transport because of the lower acceptance by consumers. To ensure that this aspect does not become a critical implementation risk for political measures, data are needed to assess environmental effects (especially decarbonisation) as well as to ensure ethical value chains. At the level of the European Union, this need has already been recognised and initial measures have been planned. However, the need for data and the way in which they are to be collected has yet to be defined.

ii Planning, practical design, and monitoring of the closed-loop recycling
The reuse and recycling of spent batteries also require a well-founded database for the efficient design of value creation and conservation. A database makes it possible to assess the further potential for use at the end of a battery life cycle, to analyse the effectiveness of recycling management, and to develop sustainable end-of-life (EoL) strategies. Actors in the recycling chain depend on valid data for practical implementation; without reliable data on the end-of-life phase, regulatory authorities are unable to monitor compliance with legal requirements or degree of circularity and recycling. Dynamic data on the whereabouts of traction batteries and the place and time of recycling, including the quality of the processes used, are particularly important in this context.

B Export of domestically produced batteries makes recycling more difficult

Electric cars can be sold on the European domestic market without import or export duties. Vehicles produced in Germany can thus be exported to other EU member states in the future. In 2018, over 42% of all new cars produced in Germany were exported to other EU countries.[230] It can be assumed that even without taking exports of end-of-life vehicles into account, a purely national implementation of recycling would almost halve the recycling rate. In addition, over 80% of German end-of-life vehicles have been exported to other EU countries and, for the most part, to third countries outside the EU for the last several years. However, at the EU level, the return of installed batteries is also subject to special additional challenges with regard to the notification procedure for cross-national transports as well as EU-wide access to information from national or EU-wide recycling management initiatives. Although the routes of new car

230 | Own calculations, based on data | See Verband der Automobilindustrie 2020.

exports are documented, large shares of end-of-life car exports are exported via channels with insufficient documentation; this means that dates and routes cannot be traced.

As a result, there is a need for action with regard to increased transparency in the export of end-of-life vehicles and a gradual expansion of the repatriation area depending on the market relevance or battery quantity. There is a need to identify national safety standards, classify dangerous goods, and set out requirements for transhipment and pre-treatment centres and clarify requirements and simplify the possibilities for cross-border transport within the European single market.

C Low return quantities at the beginning make it difficult to achieve economic efficiency in a decentralised structure

The proportion of end-of-life batteries recycled is currently still very low. However, with the decrease in battery prices and the increase in the sale and use of electric vehicles, these will increase significantly. The ramp-up until a stable response rate is achieved will take several years. This also makes it possible to predict the potential return quotas of batteries at the end of their life cycle. There is a need for action to consider second life use, return flow volume, and its distribution as well as the return structures required for this. Further details are discussed in more detail in pilot profile III "Dismantling network for traction batteries".

D Cross-company cooperation in the pre-competitive area requires improved framework conditions

Bundling material flows of batteries and their components makes sense in order to make transport, storage, and treatment both economically and environmentally efficient. This is particularly evident from the point of view of low entry volumes. For this purpose, however, distinctions between individual and cooperative approaches must be defined.

An essential framework condition with regard to the information released would be the creation of a kind of IDIS (International Dismantling Information System) for batteries. The focus should be on the credible and justifiable enforcement of claims (e.g. against insurance companies regarding fire protection standards), the limitation of incidental costs of the processes, and the provision of the necessary information and security aspects for all actors along the return logistics chain.

There is therefore a need for action with regard to the multi-layered constellations of actors, the management of battery systems, and the exchange of information. It is also necessary to identify potential business models and the necessary data requirements as well as to determine the critical and cost-driving processes along the value chain – from the end of the useful life in the automotive operation (primary life) to a potential second life to material recovery through recycling, taking into account all stakeholders.

In addition to defining the information needs of the individual stakeholders in the value chain, the needs of data owners and users (taking into account incentives for data sharing) as well as an information analysis by operational companies as a service must be determined. In addition, the necessary standards of information in the sense of an IDIS for batteries should be defined.

1.2 Focus and definitions of the pilot topic

The aim of the pilot project "Understanding the service life of the battery" of the traction battery working group is to determine the data-related requirements for the collection and provision of battery data along the product life cycle in order to increase closed-loop recycling. The specific design of the pilot project goes beyond pure tracking and tracing of the batteries and includes a comprehensive consideration of life cycle data. By making this data available (in both directions – i.e. when data is recorded and used), the transparency of the material flow is to be increased, the origin and environmental influences (in particular CO_2 emissions of the battery materials) are to be made more comprehensible, the condition and location of the battery is to be clarified, and the transfer to possible second life applications or return to dismantling and recycling centres is to be made more efficient and demonstrable.

The primary aim is to clarify how the fullest possible return of used batteries can be achieved and whether this has actually been done in practice. In contrast to Pilot profile II "Model-based decision-making platform", Pilot profile I "Understanding the service life of the battery" focuses primarily on providing the necessary and useful data. The implementation of the pilot theme serves as a common "data infrastructure" for the implementation of the other pilot topics.

Figure 34 above shows the required and potentially feasible data flow. A direct data exchange of all actors in the value chain with the data platform is efficiently designed by prior aggregation into meaningful blocks. However, the type of design also depends

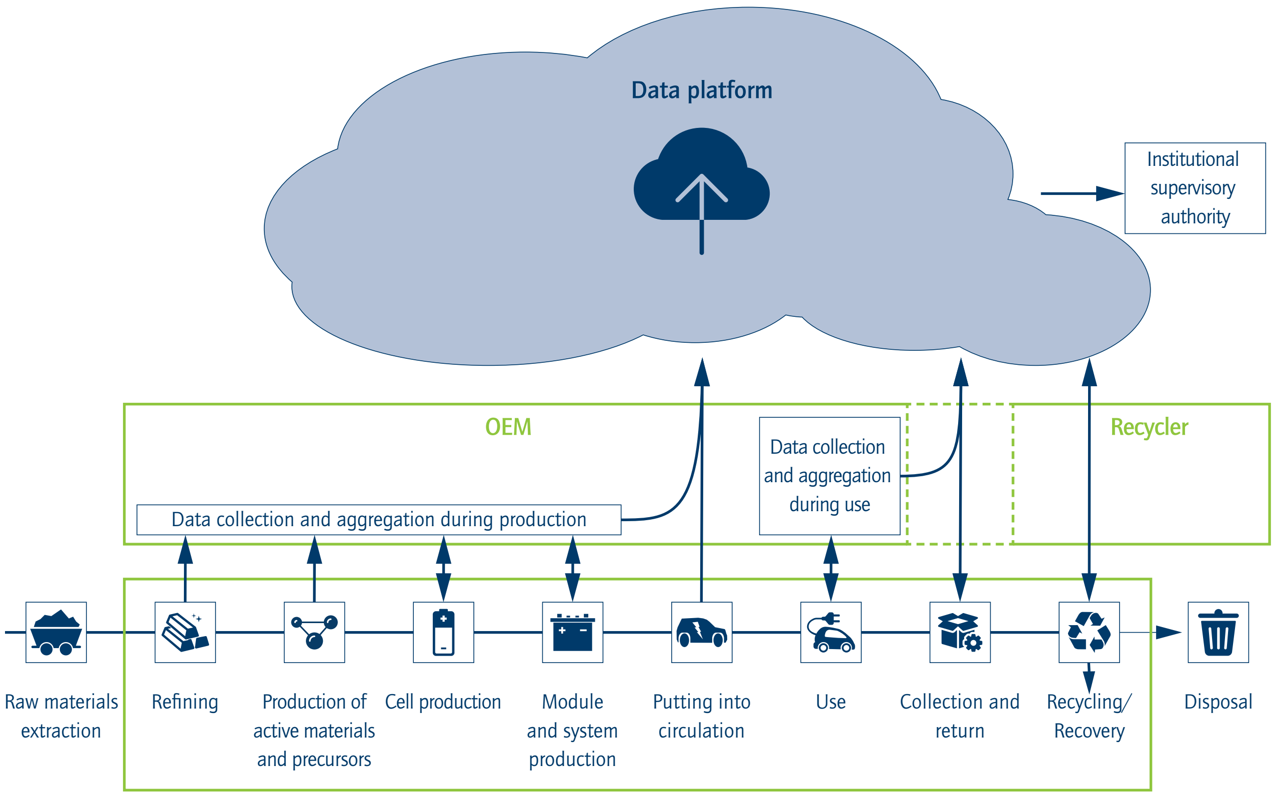

Figure 34: Information flows to promote the closed-loop recycling of traction batteries (Source: own representation, based on the representation of the World Economic Forum 2019)

heavily on the business model chosen. For example, in a leasing model in which the vehicle manufacturer or the fleet operator remains the owner of the battery throughout the life of the traction battery, data availability and traceability, the regulation of access rights, and the protection of confidential data are much simpler than in a "business as usual" model in which ownership of the traction battery changes with each sale of the vehicle. It should be emphasised that data required must be available before or at the beginning of the subsequent process step. A central and permanent data availability (but not a mandatory, permanent (live) transmission) is therefore important. The required battery data is collected via previous process steps and could be aggregated in the sense of a "digital battery twin" via different instances down to platform level. In addition, the establishment of an independent (state) supervisory body for evaluation and monitoring is advocated.

The following lists the data requirements according to the individual manufacturing steps of battery production.

A distinction is made between necessary data (which are essential for the feasibility of the battery circuits) and supplementary data (which can further increase the efficiency of the processes, the return rate, and the profitability). In addition, a differentiation is made as to whether the respective data is recorded or used in a process step.

Refinement	**Data required from the refining process:** ⇧ Raw material origin (country/mining area, if applicable); certified as "Responsible Sourcing" ⇧ Country/place/company of the refining process ⇧ Recycling content of raw materials ⇧ Environmental footprint of the refining process including preliminary stages
Production of active materials and precursors	**Required data from the production of upstream products:** ⇧ Composition and information on hazardous substances ⇧ Raw materials used ⇧ Country/place/manufacturing company ⇧ Environmental footprint of production (upstream processes, if applicable)
Cellproduction	**Required data for or from cell production:** ⇩ Composition and information on hazardous substances ⇩ Raw materials used ⇧ Cell format (pouch/round/hard case or liquid/solid electrolyte) ⇧ Cell chemistry used on the anode and cathode side ⇧ Safety relevant dismantling/recycling instructions – Cell ⇧ Test results from the end-of-line test of cell production ⇧ Date of production (calendar ageing) ⇧ Energy balance of the production ⇧ Production parameters affecting cell performance and lifetime (e.g. porosities, area capacities, forming data)
Module and systmes production	**Required data for or from module- and system production:** ⇩ Composition and information on hazardous substances ⇩ Cell chemistry used on the anode and cathode side ⇩ Test results from the end-of-line test of cell production ⇧ Production date ⇧ Risk class ⇧ Dismantling instructions – battery pack and module ⇧ Safety relevant dismantling instructions – battery pack and module ⇧ Transport container plus dimensions ⇧ Information on thermal management (e.g. maximum temperature differences in the pack, cooling rates, type of cooling)

Legend

Required data (dark blue)
Supplementary data (orange)

Data upload (⇧)
Data download (⇩)

Use	**Data required from battery use:** ⇧ Location (if the system limit is exceeded or there is a change of ownership) ⇧ Internal condition (undamaged/non-critically defective/critically defective) ⇧ State-of-Charge (SoC) ⇧ State-of-Health (SoH) ⇧ Number of charging cycles performed ⇧ Other data that may be relevant for determining the battery condition such as average depth of discharge (DoD), average states of charge, maximum and average temperature, and maximum and average currents depending on temperature (these could be obtained by intelligent cycle analysis) ⇧ Exceeding/falling below safety and performance relevant limits such as temperature, number of quick charge cycles, and deep discharge ⇧ Total stock and lifetime estimation of vehicles to determine the expected collection/return volume at time x
Collection and return	**Data required from or for the collection and return process:** ⇧ Country/place/company (data recording) ⇩ Location (data use) ⇩ Condition (undamaged/non-critically defective/critically defective) ⇩ State-of-Charge (SoC) ⇩ Information on the determination of transport regulations[231] ⇩ Transport container plus dimensions ⇩ Weight ⇩ Expected collection/return volume at time x
Recycling/ recovery	**Required specifications at system level as a basis for data evaluation:** ⇧ Country/location/company (recycling companies along the recycling chain) ⇧ Raw material whereabouts, real second life application or recycling rate achieved, proof of output masses (certified as "Responsible Recycling") ⇩ Recycling rate required by law ⇩ Types of follow-up applications **Data needed for the decision about second life:** ⇩ State-of-Health (SoH), including life cycles ⇩ Energy balance of the production ⇩ Calendar age ⇩ Condition data on materials for reuse (derating), derived from material and cell parameters

231 | Information necessary for determining the transport requirements of a battery: manufacturer, type of battery, UN number of the battery according to the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), weight, energy performance, composition and indication on hazardous substances, information on the material of the battery cover and cell, information on requirements for storage, handling and transport conditions.

	Data required for the recovery and recycling process: ⇩ Condition (undamaged/non-critically defective/critically defective) ⇩ State-of-Charge (SoC) ⇩ Cell chemistry used on the anode and cathode side ⇩ Dismantling instructions – Module ⇩ Safety relevant dismantling instructions – Module ⇩ Safety relevant dismantling/recycling instructions - Cell ⇩ Cell format ⇩ Process notes (influence of impurities; possibility of automation) ⇩ Expected collection/return volume at time x from big-data analysis

2 Success criteria for implementation

For a successful implementation of the pilot profile, the cooperation and collaboration of the actors is essential. In order to promote cooperation between the individual actors, incentives are needed for the respective stakeholder groups to motivate them to participate in the pilot depending on their interests and business models. Reliable data provision and availability as well as ensuring data protection form the basis of the correct operational design and are taken into account in the regulatory framework of the pilot concept.

2.1 Overview of actors to be involved

The actors mentioned in Table 6 are of considerable relevance for the successful implementation of the pilot topic. It should be emphasised that one actor can take on several tasks. However, for some tasks, cooperation with other actors is necessary.

Stakeholder group	Actor	Incentive for cooperation:
Suppliers/manufacturer	Raw material suppliers Battery component manufacturer Battery manufacturer Vehicle manufacturer	Legally prescribed recycling quotas, security of supply, obligation to provide evidence, responsible consumption of resources
User	Users (private/fleet users) Operator of the charging infrastructure	Performance increase through data provision/financial incentive, environmental awareness
Recycler	Workshops, logisticians Reusers, recyclers Dismantling companies/dismantling centres Recycler (recovery of raw materials)	Data/platform access for own business model in exchange with data provision for monitoring
Service provider	Service (IT, tracking & tracing, monitoring, reporting: Data infrastructure or platform operators) Research and development Service provider for second life Energy generators (stationary storage) Certifier/testing authority	Exercise/expansion of own business model (in the case of state research and certification through provision of funds)
Regulators	Legislation Approval and monitoring authorities Data protection Border surveillance (customs)	Cooperation incentives only necessary for private sector actors

Table 6: Actors involved and cooperation incentives of the pilot concept

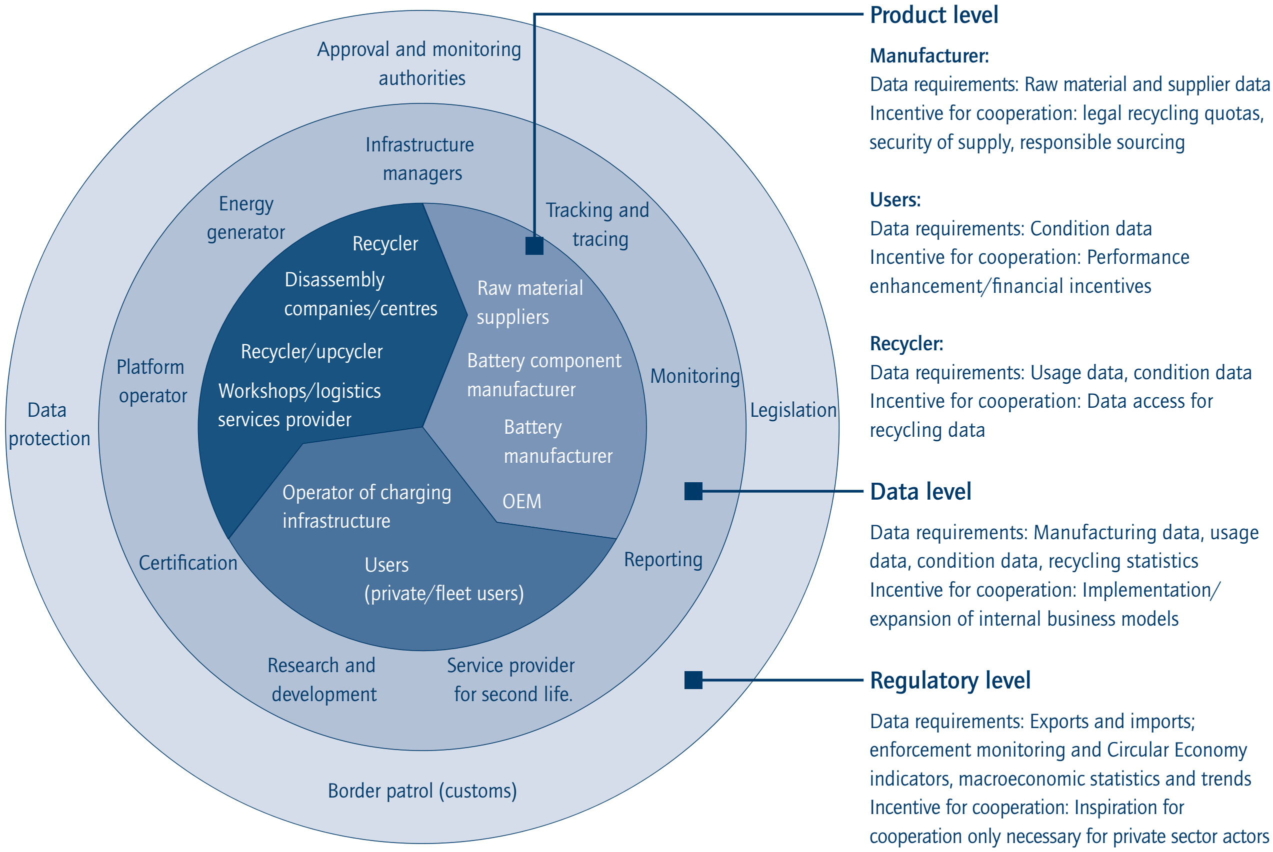

Figure 35: Actors, data needs, and incentives for cooperation for a pilot implementation (Source: own representation)

2.2 Requirements for operational design

For a successful implementation of recycling management in the field of lithium-ion batteries, it is important to involve all actors along the entire value chain and to implement the necessary steps early on. With the large number of actors (e.g. suppliers, logistics providers, vehicle manufacturers, and operators), numerous transfer points of data and physical products are created. One challenge of the pilot project is to design these transfer points in a technologically, organisationally, and economically optimised manner. This design is based on the aforementioned data, on the basis of which the decisions on further use (transfer of physical products) can be made and the success of the proposed measures in terms of the Circular Economy can be assessed (see also Pilot Profile II "Model-based decision-making platform"). The operational design of the data provision is subject to high requirements. This is because the locations and participants can vary in a cross-company and supply chain involvement.

A Data management (local versus central)

In principle, the data could be stored either locally or centrally. With a local solution, the data is stored close to the battery and is available only when it is read out by a corresponding program. This can be done, for example, in a workshop or recycling yard. However, if vehicles or batteries are taken out of the cycle (for example by export), these data are not available if the data are stored locally. In contrast, in the case of centralised data storage, the data is stored in a central location (cloud, server of the data owner) by means of a suitable IT infrastructure and can be accessed at any time by different actors. Because local data storage reduces the effort yet makes central evaluations and new approaches such as data mining or correlation analyses more difficult, a combined data storage should probably be aimed for.

B Access (role-based)

The data stored on the battery may not be read or processed in the same way by all the actors involved in the battery life cycle. Read and write rights must be defined according to the actor role. As a rule, only the battery manufacturer will store relevant information on the battery components and their design. Other information such as service information is of less importance for his role function.

C Data transparency

In addition, it must be clear and traceable who created or changed which data and when.

The following requirements arise for the central data platform of the pilot project:

Data platform

Requirements for the central data platform:

- Availability
- Structured data storage and standardised format
- Sufficient storage capacity and performance (expandability)
- Security and protection against manipulation
- Data transparency/traceability
- Role-based access
- Central access (potential for Big Data)
- Access/interfaces for reuse (e.g. Enterprise Resource Planning/Customer Relationship Management)

The respective contribution to the overall benefit of the pilot project varies for the different actors along the value chain. Maximising the individual contribution is a challenge for the company's organisation.

Here, the operating data sovereignty of the vehicle manufacturers should be taken into account because the better understanding resulting from the data offers far-reaching potential. An example of this is the efficient and thus cost-effective handling of batteries from their first use in the car to transport logistics to the re-users and subsequent end-users. A complete data situation is essential for this. The availability of data from vehicle component manufacturers on initial application and corresponding battery behaviour has therefore been identified as one of the key issues. In this respect, incentives for vehicle manufacturers to provide operating data must be increased.

For logistics (both from first to second life and final recycling), planning reliability and reduction of safety margins are a sensible and desirable result. It should be possible to estimate the availability and condition of the battery at any time and to plan transport routes efficiently.

An increase in efficiency through better economic design of the processes is a desired added value if the data is reused by third parties. The condition of the battery correlates directly with its residual value and possible reuse in secondary applications. If the data situation is known, time-consuming tests to assess the condition can be significantly reduced. In a regulated top-down approach, both research and development can benefit from the targeted data situation. If the performance and safety of current battery systems is known, future developments can be better adapted to market requirements. Because access to CAN interfaces is not possible, data is currently collected in elaborate laboratory tests and forecasts. The following points also require further consideration and should be given greater weight in the design of data handling:

Ownership and liability: So far, there are no established business models that define a clear structure of ownership of batteries and data and thus the liability risks.

Optimum for changing from first to second life: In order to estimate the market potential for second life applications, the profitability analysis from the customer's point of view must also be taken into account. It is realistic to assume that batteries will remain in their first life for a long time (about 12 years to remaining 80% State of Health). If the remaining range of the vehicle decreases because of wear and tear, users will change their behaviour or sell the car to a less demanding user. The replacement of a battery in a passenger car is economically viable only under certain conditions such as an increase in the total service life or through price incentives.

Data-driven foundation for continued stationary reuse: Much of the data required for diagnostics in the first use can also be used for the analysis and design of a second life. However, the static concept of first and subsequent second life in a stationary application is not always applicable (see above). Here, transparency is already necessary in the first life of the battery (e.g. for repairs or estimations of the battery's residual value and possible uses). Direct access via the vehicle interface (CAN bus) would be the most efficient solution. However, this is accessible only to the vehicle manufacturer.

Data owners (especially battery manufacturers and vehicle manufacturers) must therefore derive their own added value from the data provided. The identification of potentials and the incentives that go hand in hand with the provision of data are of great importance for successful implementation. A possible example of such an incentive is a cost reduction within the individual value creation stages along the life cycle.

Furthermore, the provision of data for research and development, especially for institutional providers, offers enormous innovation potential. It can also be an incentive for the customer if the purchase or resale value of a used car can be assessed in line with its value on the basis of a precise condition assessment. This also increases credibility through independent tests and expert opinions (analogous to TÜV, Dekra ...).

Aggregation of production and operating data: Another important point is the interim aggregation of data to reduce complexity and increase efficiency. This should be done in cooperation with industrial companies. Key elements are the design of data rights, data protection, and protection against manipulation. Different concepts are possible. It would be conceivable to collect relevant data from the vehicle manufacturer and then forward them to a database. Accordingly, battery parameters and usage patterns as well as safety-relevant events are available. A standardised transfer interface to the data platform could be provided here.

2.3 Requirements for regulatory framework conditions

A Relevant aspects for regulation

In addition to the collection and relevance of data, important aspects for regulation are the materials and condition-related data of the traction batteries (e.g. the materials used as well as the data on the battery system, recycling, and reuse). Similarly, a high level of data protection and privacy is of particular importance. At the usage level, the obligations to provide evidence of reuse (e.g. in deposit systems and the location of the battery for tracking to the end-of-life and along the recycling chain) represent a major challenge. Information on the recycling content, the recycling content of the battery, and battery safety (e.g. by introducing an electrical seal) play an important role in the context of reuse or recycling. In addition, aspects such as data ownership, transfer, access, validation, and protection against manipulation must be regulated.

B Possible regulations

Preferably, the provision and sharing of battery data should be based on the voluntary commitment of the actors involved and their voluntary participation. Incentives can support this approach. The development or definition of standards is also crucial, especially in view of the large number of different actors involved. In addition, a reporting obligation comparable to the reporting of consumption data from burners to the EU might be conceivable. Finally, financial incentives (i.e. bonuses or penalties) could be used to enforce and control the desired implementation.

3 Expected impact potential of the pilot project

The provision of data on the battery life cycle planned in the pilot project is expected to have positive effects for the respective owners, value-added participants, and industry at the economic, social, and environmental level. Because the future ownership of traction batteries is strongly dependent on business models that still need to be developed and can change over the life cycle, the influence on the owners needs further consideration. In principle, the support of an efficient assessment and extension of the useful life in terms of a second life application or recycling offers additional efficiency gains through economically and environmentally sensible path decisions. In addition, the data provided opens up cost-cutting potential for logistics and dismantling companies as well as for the process chain of material recovery.

A prepared data situation also offers the potential to use resources more efficiently and to promote more efficient investment and capital planning through the associated planning security. It also includes the possibility of creating transparency for consumers and political decisions.

4 Recommendations for action and roadmap

In order to be able to collect and provide the aforementioned battery data for an economic implementation and an economic/environmental and efficient regulation, the availability of data with regard to the superordinate cooperation of the different actors must be ensured, and the batteries must be assessed in terms of closed-loop recycling. In view of the large number of data providers and users, the interoperability of data must also be guaranteed by uniform standards.

For reasons of data law and corporate policy, the availability of data and the provision to third parties (e.g. for research projects) must be clearly and uniformly defined and legally secured.

Furthermore, it must be defined how the operational design of a platform is to be carried out. In other words, how (e.g. as a Platform as a Service (PaaS)) and by whom it is to be operated and developed. In the course of this, the necessary and supplementary evaluations that can support and improve the operation of the closed-loop recycling system must also be determined.

4.1 Recommendations for action for politics, industry, and the scientific community

Recommendations for action, broken down by addressee, are listed below. It is important to note that individual recommendations may require cooperation between politics, business, and science. There are also recommendations that are mutually dependent and which suggest implementation only in their entirety (e.g. in research, legislation, and application support for monitoring).

4.1.1 Politics

- Create coherence with national and international legal data requirements (waste legislation, recycling management, energy and resource efficiency, climate targets, chemical legislation/REACH)
- Enforce standardisation of markings (battery and materials)
- Set mandatory collection quotas
- Establish rules and standards for second life assessments and applications
- Define standards for high-quality recycling and make them mandatory along the recycling chain
- Create a legal basis for the tracking and tracing of traction batteries
- Create the basis for central data/platform access and use and security
- Establish a reporting and monitoring system to record and track batteries (statistics and transparency)
- Define rights and obligations for consumers (to ensure a deposit-like system; return and take-back obligations)
- Provide clear and strict rules for reuse exports
- Develop incentives to increase circularity

4.1.2 Business

- Define data requirements and availability (e.g. provide information material on how to handle the batteries as well as information on how to create a forecast)
- Define data and IP protection – with integration into data platforms
- Develop and implement data-based or data-providing circular business models
- Systematically record the advantages of a circular approach (beyond the purely monetary variables)
- Define requirements, legal framework, and interfaces for long-term cooperation
- Position yourself in relation to Reuse and second life of batteries
- Certify recycling companies
- Participate in the development of standards (recycling and reuse)

4.1.3 Science

- Analyse technical and economic potentials as well as limits of the circularity of battery materials
- Develop a target system to determine the circularity and associated effects (generally applicable parameters)
- Promote system integration and systemic optimisation of monetary and non-monetary parameters (e.g. development of an incentive system to influence battery flows in the sense of environmentally sound ("closed loop") paths)
- Quantify the benefits of data availability for the efficiency of recycling systems
- Develop models and scenarios for determining the requirements of return logistics and dismantling infrastructure
- Develop a reporting and monitoring system (with politics and business)
- Participate in the development of standards (recycling and reuse)
- Develop a data-driven foundation for the assessment of battery cells and modules with regard to second life applications (test/diagnostic procedures)
- Develop a data platform and data standards
- Determine environmental indicators to assess and improve the environmental impact and ethically correct supply chains of lithium-ion batteries

Time horizon / Work package	short term												medium term	long term
	2021				2022				2023				by 2027	by 2030
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4		
Basis for traceability of fate over the life cycle			■	■	■	■							Data integration and protection (data and IP protection, integration in data platforms); definition of reporting requirements; Development of a reporting and monitoring system (including big-data analyses) in coordination with business and politics (and integration into EU projects)	European and global harmonisation of data integration, reporting, and monitoring
Definition of data requirements and their availability	■	■	■	■	■	■	■	■						
Basics central data platform (+ access and protection)	■	■	■	■	■	■	■	■	■	■	■	■		
Development of an interoperable data platform + necessary standards				■	■	■	■	■	■	■	■	■		

Figure 36: Most important steps for the implementation of the project description "Understanding the service life of the battery" (Source: own representation)

4.2 Common roadmap

The main work packages required to implement the pilot topic are shown in Figure 36 after dividing the time horizon into short-, medium-, and long-term. Because of dependencies and interdependencies, a time shift of the work packages is possible only to a very limited extent.

Realising the pilot project to increase the closed-loop recycling of environmentally intensive battery materials requires not only the legal framework, an efficient economic and environmental regulation, new business models, and the associated data requirements and their availability but also the involvement of many different actors and a technically complex implementation. Because of the many resulting variable influencing variables and dependencies, both foreseeable and unforeseeable challenges are to be expected.

4.3 Expected challenges

Since, in principle, a considerable amount of data on the condition of a battery already exists but is not available, one challenge is to create incentives for vehicle manufacturers and other actors to share data. In a first step, this requires a clearer specification of the necessary data types as well as their availability and security. Minimum requirements regarding the regulatory framework to be observed (obligations, obligation to provide evidence, warranty regulations) must also be further defined in this context. In order to implement the pilot project successfully, (1) the macroeconomic potentials associated with the provision of battery specific data need to be more clearly related to (2) the specific business added value of the actors involved. Technical challenges also arise in the transmission of data during the dismantling and reassembly of batteries. The critical role of the end-user should also be addressed (especially if he/she is the owner of the traction batteries). In addition, the transparency and validity of the data provided on the battery life cycle must be ensured. Independent auditing and certification could therefore be useful. This applies also to the examination and safeguarding of data protection aspects and standards for all actors.

Pilot Profile II: "Model-based decision-making platform"

1 Motivation and objective

After the mobile use of lithium-ion traction batteries (TB), numerous processes with different degrees of maturity are available for further use and reuse[232] (reconditioning) or recycling (remanufacturing and metallurgy). These differ in the economic and environmental effort required as well as in the results achieved (output materials). In addition to the processes, the costs are also product-specific because batteries of different qualities (state of health) are sent to the reconditioner or recycler. The interest of the operator of the decision-making platform is to make decisions as to which treatment at the battery level (e.g. life versus recycling) is to be aimed at from an environmental and economic perspective. The structure of a required decision-making platform – in conjunction with the information available in pilot profile I "Understanding the service life of the battery" and pilot profile III "Dismantling Network for Traction Batteries" – is explained in pilot profile II.

With its central collection of knowledge and questions, this pilot profile forms a detailed supplement to this general report of the Traction Batteries Working Group and serves to initiate the basis for project tendering or implementation planning for a "model-based decision-making platform" (still in the pre-competitive framework).

1.1 Current challenges in the system

An efficient organisation of the return and the targeted use or recycling of traction batteries require a systematic approach. Companies in the recycling management sector (including logistics, dismantling, and recycling companies) are confronted with volatile prices for secondary raw materials, an uncertain and heterogeneous supply of available spent batteries, and an uncertain demand for the renewed use of mobile and stationary energy storage systems. The reconditioning or recycling of traction batteries has so far mostly required time-consuming manual dismantling. Further challenges are the currently still low and stochastically fluctuating return quantities as well as the lack of information regarding the material composition of the energy stores and energy storage systems. The recycling systems process different types of batteries together (e.g. nickel-manganese cobalt (NMC)-111 and NMC-622 cathodes), which results in supply chains that are not transparent for the secondary materials market and in which (socially and environmentally) reliable origin and material quality cannot be guaranteed.

Dismantling

The current situation in the performance of dismantling activities is characterised by a strongly manual character. In addition to a large number of variants and a complex structure of traction batteries (especially for battery electric vehicles), the volume and local distribution of end-of-use and end-of-life energy storage systems will continue to be subject to stochastic fluctuations. This is aggravated by the fact that products with traction batteries that are to be dismantled (e.g. electric vehicles) are often not yet designed for disassembly. The degree of organisation in dismantling and recycling companies can therefore generally be classified as lower than in manufacturing companies. This means that rationalisation opportunities (e.g. through optimised use of existing operating resources or through division of labour and the associated utilisation of learning effects) are not fully taken advantage of. The limits for automation in the dismantling of traction batteries or the associated products include the lack of economic efficiency because of the high technological requirements resulting from the complexity of the dismantling processes. On the other hand, the necessary flexibility is often lacking because of the heterogeneity of products and energy storage systems.

Planning of dismantling and recycling systems

An essential part of the planning of dismantling and recycling systems is the determination of important process parameters such as:

- dismantling costs and times
- dismantling depths and sequences
- the achievable reuse and recycling rates
- the achievable qualities and purities of the recovered materials (see in-depth study on Battery Recycling). The design and dimensioning of a dismantling system (e.g. number of stations, size of buffers, and number of conveyor units) for a given product range or energy storage system is also part of the planning.

Dismantling and recycling networks

Networks have an important role to play in the closed-loop recycling of products in general and energy storage systems in particular (see also pilot profile III "Dismantling network for traction batteries"). The advantages of these recycling management networks include:

- the achievement of economies of scale
- the distribution of risks and investments to several carriers

232 | See Ardente et al. 2018.

- the assurance of nationwide disposal,
- access to information provided at different points in the cycle[233]

Material flow management therefore usually involves a large number of cooperating companies (Material flow networks, supplement sources). At the strategic level, this includes the conception of regional recycling networks as well as sector-related planning and organisational approaches. On an operational level, product recovery management is to be mentioned; this aims at the reuse of products, components, and materials from old products. Production planning and inventory management models for networked production and reproduction systems are part of this.

Integrated consideration

For the planning of dismantling, reuse, and recycling systems, it is usually not sufficient to take the perspective of a single reprocessing or recycling company. Rather, the special features of dismantling, reuse, and recycling networks (material flow networks) must be taken into account. In practice, methodological approaches to the optimal management of companies and networks (e.g. on the basis of operational research approaches) have so far only been used sporadically. Commercial systems for production planning and control (as they are already used today in the production of energy storage systems) cannot be directly transferred to dismantling and recycling planning because the joint production processes often cannot be modelled. In addition, an early and valid decision must be made as to which products should be sensibly brought into a second life and which should be recycled.

1.2 Focus and definitions of the pilot topic

The implementation of a Circular Economy requires in particular the collection, dismantling, reconditioning, and reuse as well as the recycling and reuse of materials or metals from traction batteries for new batteries (closed loop). It is assumed that a Circular Economy can be implemented only cooperatively (i.e. in network structures). Such networks consist of a large number of nodes (e.g. workshops, dismantling and recycling facilities, and production companies), which are responsible for different tasks. The following objectives are pursued with the establishment of networks:

- Stabilisation of the volume by increasing the number of end-of-user and end-of-life products or energy storage facilities taken back,
- Achievement of economies of scale through the realisation of minimum quantities of old products,
- Improved dismantling and recycling possibilities through a more intensive exchange of information,
- Distribution of risks and investments among several sponsors.

Networks for reconditioning and processing thus represent value-added networks with various partners at the inter-company level in order to coordinate material flows that arise in connection with redistribution, dismantling, reconditioning, and processing, both in terms of economic and environmental target criteria (macro perspective, see also Pilot Profile III "Dismantling Network for Traction Batteries"). The most urgent task at the operational level is to make short-term decisions on the relevant material flows

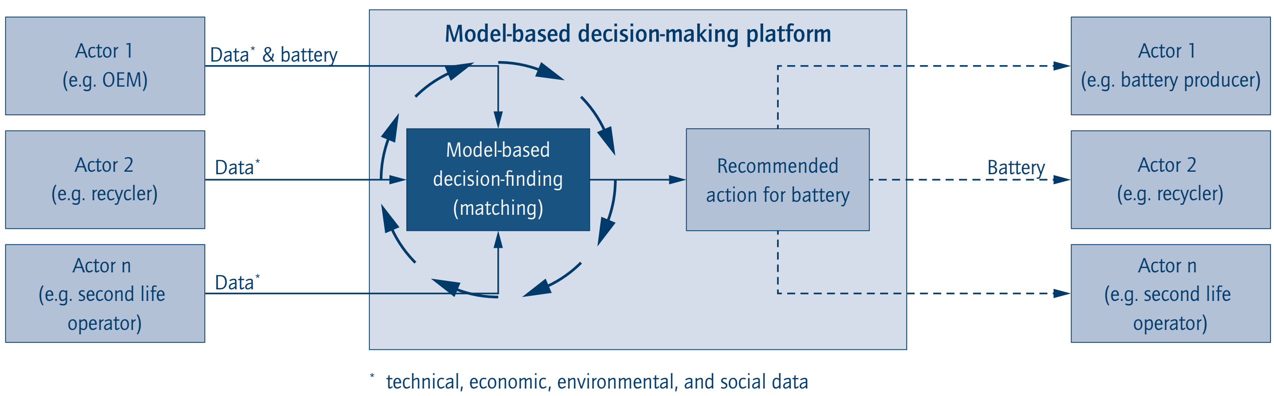

Figure 37: Concept of the model-based decision-making platform (Source: own representation)

233 | See Steinborn et al. 2010.

in the network. While the design of networks at the strategic level requires average expected future framework conditions, the operational steering task entails the continuous adaptation of material flows within the network to fluctuating quantities, recycling revenues, and capacities over time as well as changing legal framework conditions. Complementary to this, decisions on the technical and organisational design of these facilities must be taken at the level of individual dismantling and recycling facilities (micro-perspective). The model-based decision-making platform required for decision making can be structured in accordance with Figure 37.

The actors of the platform provide individual data on supply and demand, among other things. Within the platform, a decision-making process or a "matching" of supply and demand can take place under various framework conditions such as quality requirements. The used traction battery can then be transferred to the appropriate actor according to the recommendation of the platform. The more precise structure of model-based decision making and the parameters taken into account are presented in Figure 38. In the visualisation level (Graphical User Interface, GUI), the model-based results are prepared and presented in a stakeholder-specific way (the icons used in the figure represent exemplary visualisation options).

The basis is a data level with information on the current product, process, and market as well as the legal framework (Table 7). The data and information form the basis (input) for developing suitable decision rules or models (logic level). Essential data and areas of information (see also pilot profile I "Understanding the service life of the battery") are:

- Product information[234] (e.g. on material composition), product structure, joining techniques used
- Process information (e.g. dismantling and recycling technologies available), process paths, recovery rates, quality and purity of the recovered materials, substances, metals
- Market information such as volumes of end-of-user and end-of-life storage, raw material prices, demand for second life batteries, and achievable prices
- Information on laws and regulations – for example, recycling rates and qualities to be observed (see in-depth study on battery recycling)

Within the logic level described below, socio-economic and environmental models are used in combination with a flowchart simulation and a decision tree in order to identify the optimal end-of-user and end-of-life treatment. With the help of the platform, a model-based decision must be made as to whether mobile energy storage units are to be reconditioned, reused (second life)

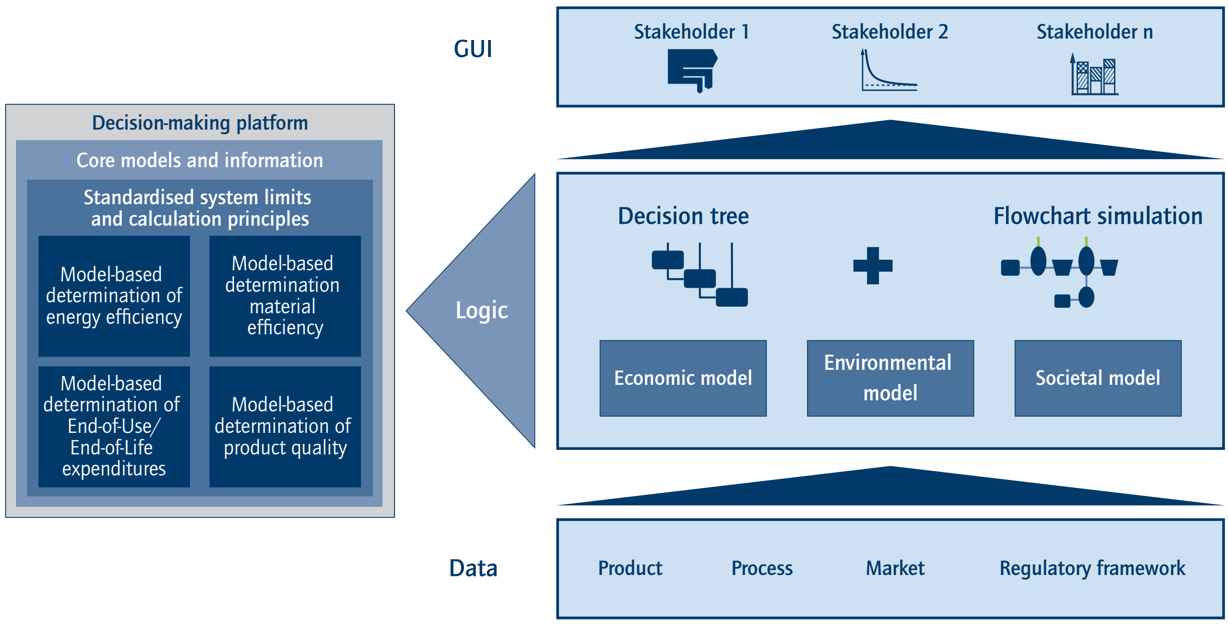

Figure 38: Model structure of the decision-making platform (Source: own representation)

234 | See Europäische Union 2019.

or recycled (see Figure). This decision often results from the chosen optimal dismantling depth.[235] This in turn depends on the residual value as well as the expected expenses and revenues. In accordance with the EU Waste Framework Directive,[236] the decision tree shown prioritises reuse over recycling. In recycling, high-quality (battery) material recycling for reuse in batteries (closed-loop) is preferred to material recycling for other industries and applications (open-loop). The decision support is based on a physical-chemical flowchart simulation, which compares different end-of-user and end-of-life scenarios on a model-based basis and determines an optimum.

The simulation-based foot-printing of processing facilities and systems was developed by one of the authors of the document in a commercial software tool, HSC Sim[237] and was applied, among other things, to the assessment of large recycling systems as

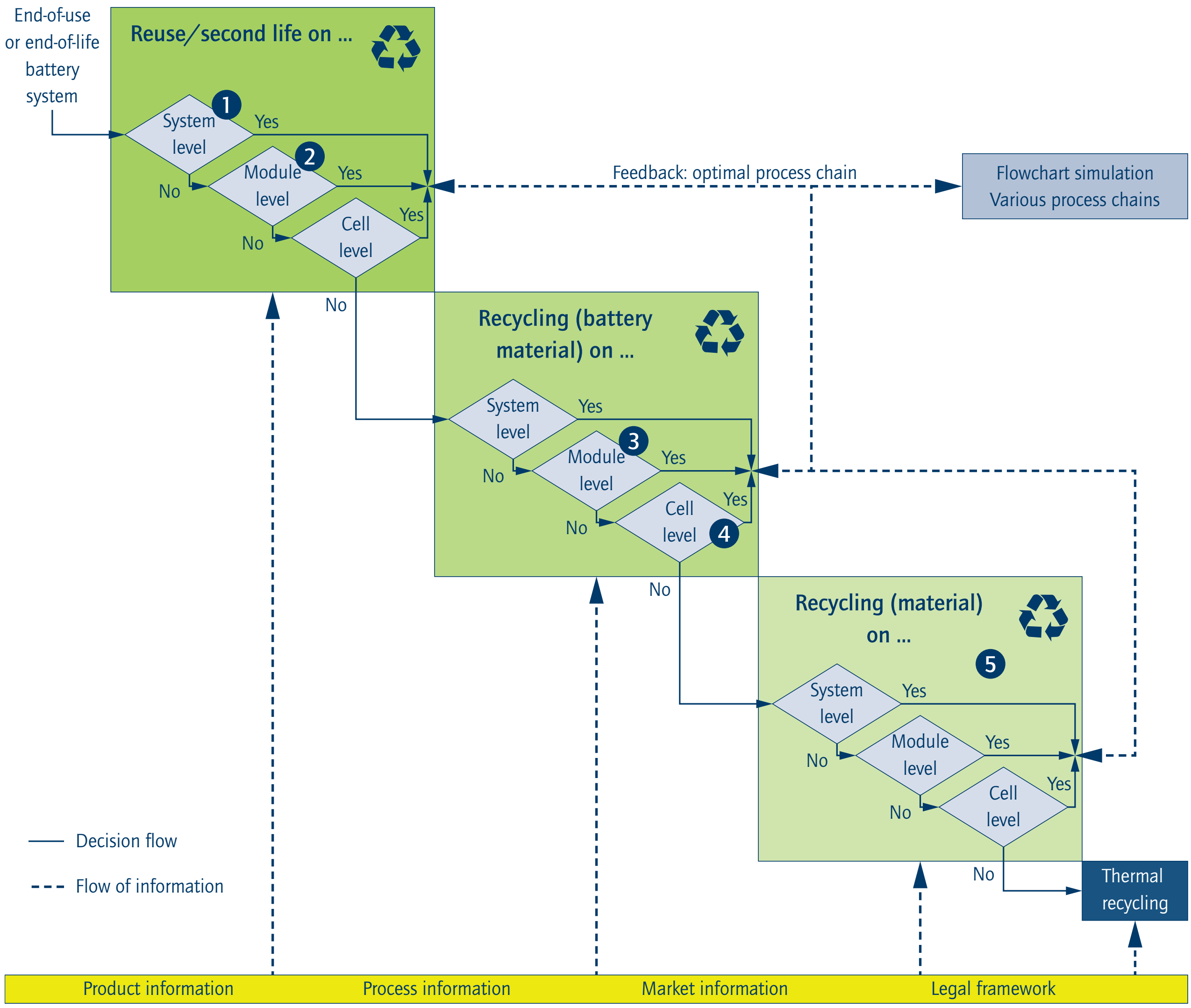

Figure 39: Decision logic - combination of decision tree and flowchart simulation for decisions at the company level (micro level) (Source: own representation)

235 | See Ohlendorf 2006.
236 | See Europäische Union 2008.
237 | See Outotec.

discussed in recent publications.[238] The strength of the approach lies in the fact that, based on the process technology and its flowchart, physics, and chemistry (Gibbs free energy, phase equilibria, kinetics, transfer processes), supply chains can be digitally linked – even if not all production data is fully available.[239] Based on the rigorous mass and energy balance, the data is exported to life cycle analysis tools, which also allow exergy analyses to be carried out in order to be able to fully understand the true losses from the recycling system. In addition, different processing routes can be rigorously compared in order to identify which options are optimal for minimising losses from the battery recycling system.

An example of reuse at the system level is stationary energy storage systems for peak load coverage in the energy sector. For example, the battery systems as a whole are recombined in a container solution and connected to the grid (see Figure 39, 1). If the battery systems are disassembled at module level, individual modules can be combined individually and used – for example, to cover peak loads in the energy sector or in standard household stationary storage units of photovoltaic systems (see Figure 39, 2). Reuse and recombination at the cell level are also conceivable. The recycling processes can be roughly broken down into the processing of batteries at the system, module, and cell level on the basis of their size and robustness as well as demands on the required output quality. Thus, (mechanical) remanufacturing can currently be carried out both at the module level (see Figure 39, 3) as well as at the cell level (see Figure 39, 4). These processes are currently being further developed in numerous ongoing research projects. In addition to the recovery of directly reusable battery material for renewed battery production (see Figure 39, 3+4, closed loop), open market recycling can also be pursued (see Figure 39, 5, open loop). Established process routes and those currently under research can also be differentiated based on the target materials. Some routes focus on the metals they contain – especially nickel, manganese, and cobalt – while other routes also specialise in the recovery of organic components such as graphite and electrolyte components. The classification of the processes does not distinguish between the different system sizes on the market (e.g. hybrid vehicles versus battery electric vehicles) but rather provides a general possibility for differentiation and decision making.

In addition to supporting decisions at the level of an individual dismantling and recycling company, the pilot topic will also focus on integrating the macro/network level with the micro/company level in the decision-making platform. Accordingly, the following aspects must be taken into account:

- Design of ideal dismantling principles for a given volume of energy storage
- Development of a material flow model that is able to map existing as well as ideal dismantling and recycling structures
- Conception of an operative steering approach for the economically efficient allocation of material flows to dismantling and recycling companies in the network
- Determination of optimal adaptation strategies for existing dismantling and recycling structures

The integration of the two planning levels can be achieved by identifying weak points in the network on the basis of a steering methodology in order to initiate a redesign or adaptation of the dismantling and recycling systems at the design level. In order to assess and compare alternative strategies, not only battery data and indicators (see also pilot profile I "Understanding the service life of the battery") should be used but also investment and cost estimates as well as indicators such as throughput, throughput time, inventory developments, contribution margins, and flexibility. On the other hand, an environmental assessment was to be used to quantify the environmental benefits of a Circular Economy 2.3).

The results obtained at the logic level are then processed, compressed, and conveyed in an understandable way using visualisation methods (graphical user interface, GUI) adapted to the stakeholders. The focus here is on the compression and

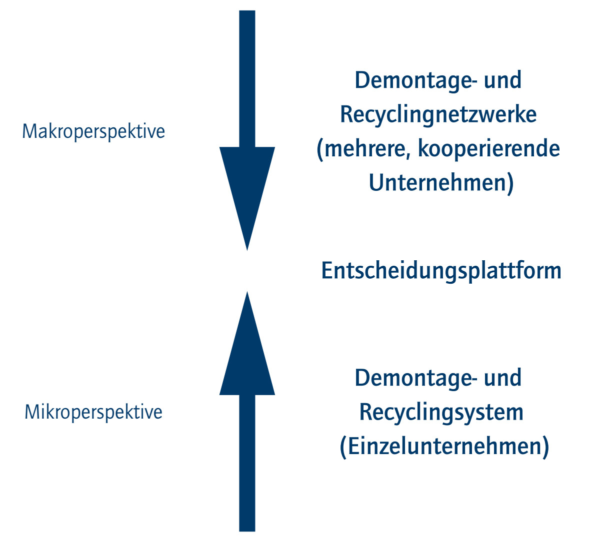

Figure 40: Integration of the network and company level in the decision-making platform (source: own presentation)

238 | See Bartie et al. 2020.
239 | See Reuter 2016.

visualisation of the key performance indicators calculated with the help of the models.

This pilot profile summarises the following aspects:

- Development of an open platform to model the optimal end-of-life use of traction batteries, whereby the optimisation path is based on technical, socio-economic, and environmental criteria.
- The pilot project initially includes the basic decision of whether the batteries will be reused in second life applications or fed into the material recycling process.
- In the case of battery recycling, the aim is to provide assistance in selecting the optimal recycling path.
- In contrast to Pilot Project I "Understanding the service life of the battery", the focus of this project should go beyond technological data and include socio-economic and environmental target parameters in the decision-making process. The implementation of Pilot Project III "Dismantling network" is to be included in the modelling as a corresponding data input.
- Creation of preconditions (especially improved data situation) to enable meaningful life cycle costing (LCC) and life cycle assessments (LCAs) as well as a Circular Economy in the physical sense. To this end, the greatest possible transparency must be maintained ("white box").

2 Requirements of the decision-making platform

According to Figure 38 , the requirements for the decision-making platform can be divided into the requirements for the data level, the logic level, and the visualisation level and are described generically below.

2.1 Requirements at the data and information level

The basis of the decision-making platform is a data and information level on which representative data is collected in order to be able to carry out meaningful modelling with subsequent decision support. The data availability is based on systematically and continuously collected data along the battery life cycle (see also pilot profile I "Understanding the service life of the battery"). The data can be broken down into product or battery data, process data, market data as well as regulatory conditions such as required minimum quotas. For valid modelling, these data must be available in as much detail as possible; this can represent a challenge. According to Figure 37, the platform should allow certain actors to contribute the respective case-specific data themselves within their area of expertise. For this purpose, Table 7 provides exemplary data and information, which are used in the decision-making process.

2.2 Requirements for the design of the logic level

Against the background of the complex decision situation, a model-based approach for a decision-making platform is proposed. Both physical-analytical and empirical (data-driven) models can be used. The design of the logic level, starting from the network level, is intended to support strategic decisions at the level of individual dismantling and recycling companies as well as operative decisions on specific recycling paths (recovery versus use, recommendation on alternative recovery paths).

Product information	Process information	Market information	Regulatory framework
▪ Cell format ▪ Cell chemistry and metal content ▪ State of Health (SoH) ▪ Age ▪ Use	▪ Energy requirements ▪ Emissions (air, water, soil) ▪ Occupational safety ▪ Material efficiency (also for individual key materials) ▪ Resource efficiency ▪ Real output quality ▪ Flexibility ▪ Capacity and utilisation rate ▪ Degree of maturity	▪ Current qualitative and quantitative offer and prices of traction batteries ▪ Distribution of supply in the market ▪ Demand for raw materials and prices ▪ Current qualitative and quantitative demand for and prices of second life applications ▪ Market development	▪ Minimum collection rates ▪ Minimum recycling quotas ▪ Minimum use of secondary material in production (recycled content) ▪ Deposit system ▪ Other incentives (for second life)

Table 7: Exemplary information for decision making

Technical assessment

The model development and integration requires realistic considerations of the mass and energy balance, exergy losses within the system, and the "hidden costs" resulting from the mixing of material flows and composites. Existing Circular Economy approaches (e.g. of the Ellen MacArthur Foundation)[240] do sufficiently consider exergy and dissipative losses and often fail to take real application-specific challenges into account. Therefore, specific, real, current, and validated data must be implemented in the model. Among other things, this will enable a realistic comparison of different process technologies.[241]

Economic assessment

The realistic considerations described in the technical assessment will also be used for the economic assessment in order to make more valid forecasts and cost calculations. In this respect, reduced sales values resulting from material mixtures and impurities are taken into account – as are energy losses. The quality and purity of the recyclates produced has a significant influence on both process costs and achievable prices.

Environmental-social assessment

An environmental-social assessment of the Circular Economy requires a transparent discussion of who should bear which burdens and reap which benefits in a specific recycling or second-life application. In this context, it is necessary to clarify by way of example who can be credited for the reduced environmental performance of a secondary material when it is re-integrated into production – and to what extent. A further example is the retroactive consideration of the extension of use through second life applications to the environmental performance of first-life applications and the associated intensive production. Only a standardised evaluation scheme allows environmental-social comparisons to be made and overarching system optimisation to be achieved. A mere shifting of problems (burden shifting, rebound effects, trade-offs) should be avoided at all costs.

In the context of holistic optimisation and the avoidance of a problem shift, a mere consideration of the greenhouse gas emissions is insufficient. Other indicators such as acid potential (AP) and human toxicity potential (HTP) must also be taken into account in the decision-making process. If necessary, further meaningful indicators must be determined. In particular, the identification and application of social and cycle-oriented indicators still require further research. In general, an environmental-social assessment must weigh up the completeness and the effort required. The aim of the pilot topic is to consider and further develop methods of life cycle assessment (LCA) and social LCA within decision support.

Holistic considerations about the logic of the pilot project are made in summary. These aim at an economic and environmental optimisation.

2.3 Requirements for the design of the visualisation level

The visualisation of the results with regard to the preferred end-of-use and end-of-life treatment should be based on comparable indicators (see Section 2.2) and be compact and easy to understand. The following examples of key figures can be taken into account, whereby a mass (e.g. kilograms of battery) or capacity reference (e.g. watt-hour capacity) of the indicators should be sought:

- Achieved battery capacity for reuse or second life
- Achievable recycling yields and qualities (of battery materials and/or individual metals and materials)
- Energy efficiency (kilowatt hour per kilogram of battery)
- Greenhouse gas emissions (kilogram of CO_2 per kilogram of battery)
- Acidification potential/human toxicity potential or similar
- Costs (Euro hour per kilogram of battery)
- Revenue (Euro per kilogram of battery)

3 Success criteria for the implementation

The success criteria of the decision-making platform result from the potential operator, his/her motivation, and the actors of the platform considered. The operator may have state or public, scientific or private sector structures, which is why the structure and processes of the platform may vary. However, in order to substantiate the design of a model-based decision-making platform within the framework of the pilot project, three potential platform operators from different sectors will be explained below by way of example:

1. Vehicle manufacturer
2. Authority or public authority
3. Other private sector operators

The vehicle manufacturer can operate a platform adapted to his structures with individual interests. The platform can also be operated across products and manufacturers by a state authority or public sector (e.g. Federal Environment Agency). In addition to the

240 | See Ellen MacArthur Foundation 2020.
241 | See Reuter et al. 2019.

	Platform operator		
	Vehicle manufacturer	State/public	Other private sector
Motivat ion	▪ Reduction of costs and environmental effect of traction batteries ▪ Securing of raw materials and reducing the influence of raw material price fluctuations ▪ Better assignment of traction batteries to second life applications ▪ Assurance of recycling rates and quality ▪ Proof of recycled content ▪ Marketing ▪ Data sovereignty and data protection	▪ Optimisation of value creation, competitiveness, and sustainability in Germany ▪ Optimisation of networks ▪ Integration of all manufacturers and actors ▪ Securing of raw material for the economy ▪ No economic self-interest and independence	▪ Use of data values ▪ Generation of profits with the platform operation ▪ High customer interest (platform users) ▪ Extensive independence ▪ Better international opportunities for action
Business model	▪ Cost savings and increased material availability through increased recovery in recycling and increased use of second life applications ▪ Reduction of end-of-life provisions through improved forecasts of second-life potential ▪ Secondary benefits (image enhancement, risk mitigation) through improved environmental performance ▪ Additional business models for – and influence on – the downstream market of batteries	▪ No viable business model necessary ▪ Financing via producer levies (for example) is conceivable ▪ Objective: Improvement of value creation, competitiveness, and sustainability in Germany	▪ Collection and reprocessing of data and provision of a database (e.g. for life cycle assessment) ▪ Trade with data sets and evaluations ▪ Consulting
Success criteria	▪ Validation and comparability of different platforms by certified testers ▪ Data and decision transparency ▪ Involvement of all relevant actors and information ▪ Interface for data access from outside ▪ Profitability of the platform ▪ Individual decision for used traction batteries ▪ Optimised life cycle of the traction batteries	▪ Data protection and protection of company interests ▪ Storage location and transparent use of data ▪ Operation and maintenance of the platform ▪ Involvement of all actors and information ▪ Standardisation and validation of data ▪ Access to multinational companies (even if the headquarters are outside Germany/EU) ▪ Safeguarding of knowledge, old equipment and secondary materials in Germany ▪ Interface with other national platforms (where appropriate)	▪ Data protection and protection of company interests ▪ Storage location and transparent use of data ▪ Involvement of all actors and information ▪ Access to the platform and database ▪ Standardisation and validation of data ▪ Profitability of the platform ▪ Holistically sustainable approach

Table 8: Design of the decision-making platform depending on the operator

operators mentioned above, the platform may also be operated by a private company (independent of the vehicle manufacturer).

The following Table 8 lists the operator-specific motivation and a potential business model as well as the requirements and decision criteria of the platform.

3.1 Overview of motivation and business model of the platform operator

An operator-specific development of the platform results from different motivations and business models. The business models can be based, among other things, on the trade in data/evaluations or on social or industrial (e.g. in the form of a producer levy) financing.

Table 8 lists the possible motivations and business models of the various operators.

A possible platform design with a business model that pursues the optimised matching of individual supply and demand is demonstrated below in Figure 41.

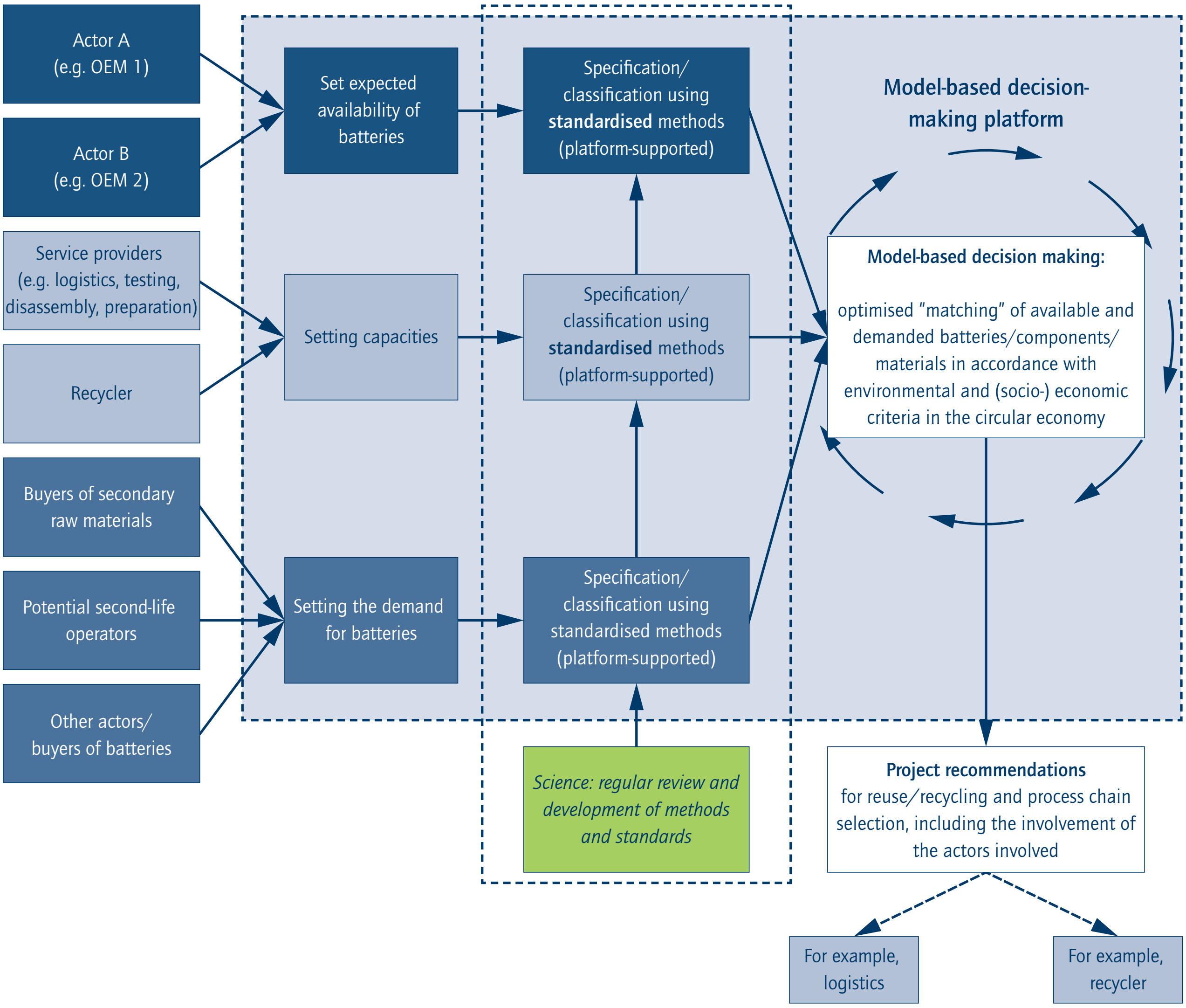

Figure 41: Schematic representation of the integration of a platform into business processes of the Circular Economy (Source: own representation)

Science plays a special role here because it can evaluate existing methods and results as a cross-sectional function and is also responsible for updating the methods on the basis of the latest findings.

3.2 Overview of actors to be involved

The identification and classification of actors and stakeholders of the platform requires a structured analysis and is highly platform-specific.[242] The stakeholder analysis must include the identification ("who") and the reason for the interest in the platform ("why") as well as the enforcement of interests or influence on the platform and other stakeholders ("how"). As a first step, Table 9 lists relevant actors to be considered in the implementation of a decision-making platform for used traction batteries.

Possible interests of selected actors in relation to the decision-making platform

- **Raw material supplier (primary and secondary)**

  The raw material supplier is interested in market developments with regard to first and second life applications as well as the resulting supply, demand, and price developments of primary and secondary materials. The raw material supplier

242 | See Ashby 2016.

Stakeholder		
in the material flow	on the periphery	in regulatory systems
▪ **Raw material supplier (primary and secondary)** ▪ Component manufacturers ▪ **Battery manufacturer** ▪ **Vehicle manufacturer** ▪ **User (first and second life)** ▪ Workshops ▪ Logisticians ▪ Dismantling companies/centres ▪ **Reconditioner** ▪ **Recycler**	▪ Service providers (IT, tracking and tracing, monitoring, reporting: data infrastructure) ▪ **Platform operator** ▪ Service provider for second life ▪ **Science** ▪ Certifier/testing authority ▪ Energy generators (stationary storage)	▪ **Legislation** ▪ **Approval and monitoring authority** ▪ Data protection ▪ Border surveillance (customs)

Table 9: Relevant actors for decision-making platform

also shows interest in achievable secondary qualities. This knowledge enables the supplier to manage capacities and prices.

- **Battery manufacturer**
  The battery manufacturer is interested in market developments regarding its supply chain. The battery manufacturer also has great influence on possible end-of-user and end-of-life scenarios through the design and manufacture of the battery, whereby there is a clear focus on first-time application.

- **Vehicle manufacturer**
  The vehicle manufacturer is interested in ensuring that the batteries taken back are reconditioned or recycled (if necessary by a third party) in the best possible way in order to achieve the highest possible economic and environmental yields or credits. The platform could be used to demonstrate the share of responsible sourcing and recycling and to achieve greater independence from raw material price fluctuations through cycle-oriented service offers (e.g. leasing models with reuse and recycling as a service). The platform can also be used to reduce costs and risks by transferring end-of-user liability and capital expenses (regarding liability, provisioning risks and capital costs) to second life users. The platform can also be used for marketing purposes (green image).

- **User (first and second life)**
  The user of a first or second life application is interested in obtaining a certified, high-quality, and sustainable product as well as in achieving the highest possible sales price or low disposal costs after use. Through his/her purchase decision and the provision of usage data, the user has influence on the platform.

- **Reconditioner**
  The reconditioner is interested in market developments regarding used batteries offered and second life applications required. The reconditioner is also interested in quality requirements and quality predictions of the applications. The platform enables the reconditioner to offer high-quality used batteries; batteries of lower quality (e.g. residual capacity) are sent for recycling. Through the design and efficiency of the reconditioning, it exerts a high degree of influence on the decisions of the platform.

- **Recycler**
  The recycler is interested in market developments regarding the used batteries offered and the demand for secondary materials. Because of technical equipment and the resulting energy and material efficiencies and qualities, the recycler has considerable influence on the decision-making process of the platform. With the help of the platform, the recycler can realise an optimal process design and produce products with high economic and environmental benefits.

- **Platform operator**
  The platform operator is interested in the added value of the platform for the other actors (if different from the actors mentioned). By structuring and defining the decision logic, the operator has considerable influence on the platform.

- **Science**
  Science has a strong interest in transparent and objective decisions regarding optimal end-of-user and end-of-life treatment. By developing standardised methods and tools, it lays the foundation for decision logic and has an interest in its further development.

- **Legislator, licensing and supervisory authority**
  The legislator and the supervising authorities are interested in maintaining critical materials and end-of-user and end-of-life competencies in Germany and Europe as well as in increasing the value added. Furthermore, the legislator sets climate targets and is therefore interested in reducing emissions through circular value creation. Through the aforementioned regulations and laws, including those relating to data security and governance, it provides the framework for the platform.

The tasks described are partly assigned to several actors; several tasks are partly the responsibility of a single actor. The next step is to disclose the respective interests in and influences on the decision-making platform. The influence and interest of selected actors on the decision-making platform are visualised in Figure 42.[243]

The presentation of the actors is highly individual and can depend on the platform as well as on the type of actor and must therefore be worked out specifically for each case. For example, the influence of individual actors changes if the platform is operated by the state instead of the private sector. This can also have a major effect on the selection and interest of actors.

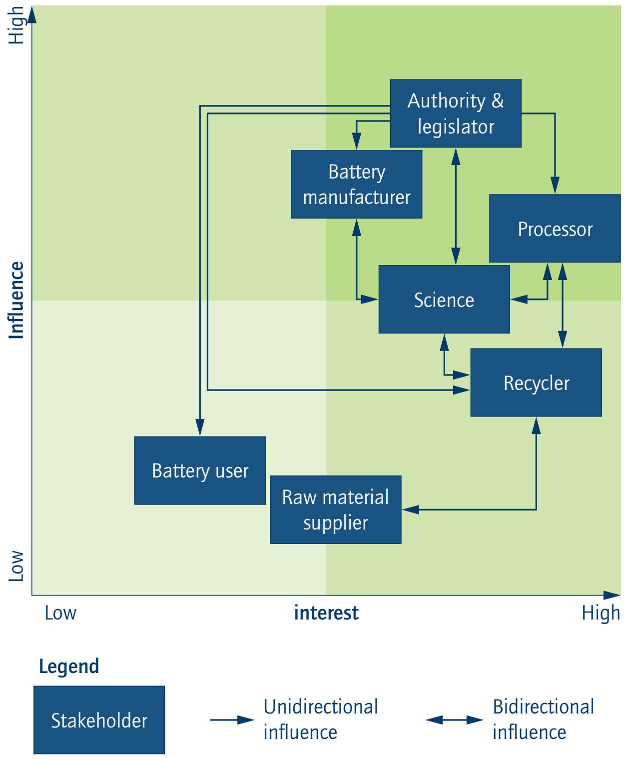

Figure 42: Influence and interest of the actors with regard to the design of the decision-making platform (Source: own representation)

3.3 Success criteria for the decision-making platform

In order to successfully implement the decision-making platform, the logic level structure must be valid and fair for broad acceptance. Standardised methods as well as fair system boundaries, among other things, with regard to the distribution of charges and credits in second life and recycling,[244] are to be developed for this purpose. The success of the model-based decision-making platform is measured by the increasing interest and influence of the individual actors in the platform and thus a support of the Circular Economy (see Figure 42). There are also operator-specific success criteria (see also Table 8).

Vehicle manufacturers as platform operators

Various vehicle manufacturers could develop parallel platforms for their networks. It should be ensured that the platforms are comparable with each other and subjected to independent certification. For the greatest possible success, the involvement of all relevant actors and their data as well as transparent decision-making is essential. Another criterion for success is the profitability of the platform (i.e. contribution to cost savings and environmental impact over the optimised life cycle of the traction battery).

Authority and public authorities as platform operators

For a successful, state-operated central platform, data protection and the safeguarding of company interests and storage location as well as the transparent use and transfer of data must be ensured. For central data management, the data must be standardised and validated. For a successful implementation, multinational companies located in Germany should be considered in addition to national companies. The success of the platform can be measured by the safeguarding of knowledge, old equipment, and secondary materials in Germany.

Private sector platform operator

Through the potentially centrally designed platform, the success criteria of a private-sector platform refer to the criteria of both a vehicle manufacturer and a state-operated platform. For the platform as such to be successfully implemented, it must be profitable as a service and easy to use for the actors. There must also be incentives for the actors to make their data available.

243 | See DIN EN ISO 14040:2009-11 2009.
244 | See ibid.

4 Expected impact potential of the pilot project

- At the *macroeconomic and societal level*, such data-based modelling can help to quantify policy recommendations with clear targets (such as setting specific recycling rates – for example, X percent of lithium from batteries must be recycled).
- At the *business management level*, individual actors can develop company-specific scenarios on the basis of the open and modular model, incorporating internal data, and determine the optimal end-of-life use without having to make confidential information public.
- The scenarios developed can help make robust decisions regarding the optimal dimensioning of new recycling facilities and the right time to invest.

4.1 Impact on the vision 2030

In order to operationalise the transformation to a decarbonised, Circular Economy, the participants of the Traction Batteries working group developed a common vision along the following five dimensions. These should take into account the resource productivity targets for 2030[245] defined in ProgRess III.

- Regulatory systems
  - A (central) platform guarantees data protection and security.
  - A key figure-based disclosure of the potential of the Circular Economy promotes and harmonises high-quality reuse and responsible recycling.
  - A standardised procedure – which can determine and credit the recycled shares of the raw materials available on the market – enables accurate, realistic, and (for consumers) transparent environmental assessments of batteries.

- Material flows
  - Knowledge of the regional location, quantity, and quality of the traction battery through tracking and tracing tools provides an important component for capacity and logistics planning.
  - Secure databases within the platform with standardised interfaces and data as well transparent protocols provide actors along the value chain with customised information while ensuring the protection of intellectual property and competitive advantages (see International Data Spaces). Private sector solutions complement those of the public sector.
  - Relevant research and development on battery ageing, testing, and safe handling has led to clarity on the extent to which vehicle-to-x (V2X) and second life applications of traction batteries make economic and environmental sense. Within the decision-making process of the platform, second life applications gain importance.
  - All traction batteries are collected at the end of their useful life and, after possible maintenance and/or, where appropriate, a further life (if necessary in stationary use) are ultimately recycled in an efficient and high-quality manner. The platform provides important decision-making support for the selection of the best possible treatment.

- Technical development
  - Design for circularity and design for recycling have become the industry standard and enable circular business models as well as the increase of real recycling rates.
  - The widespread use of tracking and tracing technologies (battery passports and Circular Economy data spaces) and the versatile integration into business (IT) systems ensure the reliable provision of information about the whereabouts of the batteries while guaranteeing data protection and security.
  - The modular design of batteries – in part also between different battery system manufacturers – helps to make the repair, reuse, and recycling of battery (components) efficient.
  - The increasing automation of maintenance and dismantling lead to the scaling and cost reduction of reuse and end-of-life measures.
  - Compared with 2020, recycling technologies are significantly more (energy) efficient, economical, safe, and effective (especially in terms of yield and purity) in the production of high-quality recyclates. This means that the majority of the materials can be recovered in a high-quality and economical way. A largely automated flowchart simulation supports the optimisation by disclosing hotspots and comparing with other technologies and processes.

- Value networks
  - The platform contributes significantly to the cooperation of the actors and the superordinate optimisation of the network – for example, by means of a usage extension and cascade management as well as a high-quality closed-loop recycling of battery materials.

245 | See Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2019.

- Batteries are managed across actors over their entire life cycle, thereby creating entirely new business models and constellations of actors.
- New roles for existing actors (no classic thinking in upstream and downstream) and completely new fields of activity with new market actors are developing. Through the fair distribution of expenses and credits within the networks, the platform creates a high level of acceptance among the actors.
- The widespread use of digital platforms for batteries and their materials has led to a high degree of transparency and market efficiency, thereby enabling a variety of new business models for new and old market participants.
- This is accompanied by a strategic and operational integration of the energy and transport sector in the sense of sector coupling. This is supported by sustainable technological and social trends (especially electromobility, energy turnaround, and industry 4.0). The decision-making platform takes into account the interlocking of the mobility and energy turnaround through the best possible utilisation of second-life applications such as stationary storage systems.

- Internal implementation
  - The establishment of effective dismantling networks (dismantling, assessment, transport) has led to the efficient and safe handling of the rapidly increasing quantities of end-of-use and end-of-life batteries. The early management of the market ramp-up of the dismantling facilities through the support of the platform has resulted an efficient combination of decentralised and centralised sites and systems.
  - New holistic KPI systems (economic, environmental, social), which appropriately reflect new circular business models and their value flows at the organisational and product level, have found widespread application and are published and tracked according to their contribution to the achievement of (inter)national targets for resource productivity and efficiency.

4.2 Possible exchange relations (trade-offs)

Conflicting objectives are to be expected in decision support because the environmentally preferable treatment of used batteries does not necessarily have to be the most economically and commercially sensible. This can be illustrated by the dismantling depth in the remanufacturing as an example. The deeper the dismantling process, the potentially purer the components and materials contained can be separated, although the environmental impact caused by often manual processes is minimal. At the same time, manual processes, especially in high-wage countries, mean high preparation costs[246, 247] and thus reduce the economic efficiency.

Technical feasibility must be ensured as a basis for the decision-making platform. Therefore, the overriding objectives as well as their hierarchy and weighting are essential for sustainable and socially accepted decision support. It is not possible to implement the Circular Economy on the basis of local economic factors alone as they are generally currently used. In line with the goal of sustainability, the environmental and social aspects of decision support should therefore be strengthened in addition to the economic aspect. In the sense of corporate responsibility for society as a whole, the environmental and social aspects must be given equal importance to economic interests or – as far as reasonable – be given priority over them. In order to maintain transparency and objectivity, all indicators should nevertheless be presented.

5 Recommendations for action and roadmap

Based on the exemplary decision platforms described above, recommendations for action can then be made and a roadmap for the further development of a decision-making platform within the Circular Economy can be defined.

5.1 Recommendations for action for politics, industry, the scientific community, and civil society

Recommendations for action can be defined for four target groups (politics, business, science, and civil society), some of which are platform operator-specific. The recommendations for action are summarised below in Table 10 .

246 | See Canals Casals et al. 2016.
247 | See Kwade/Diekmann 2018.

	Platform operator		
	Vehicle manufacturer	Authority/ public authority	Private sector
Politics	▪ Standardisation of calculations, evaluations, and interfaces ▪ Certification ▪ Incentives for second life applications ▪ Data protection and confidentiality ▪ (Political) recommendations for action with quantified targets		
Politics		▪ Financing and control of the platform ▪ Transparency and easy use of the platform ▪ Development of a platform with data interfaces and data restrictions	
Business	▪ Creation of demand markets ▪ Standardisation of calculations and data interfaces ▪ Organisation in networks ▪ Cooperation with science		
Business	▪ Financing and control of the platform ▪ Data protection and confidentiality of third parties ▪ Development of a platform with data interfaces and data restrictions		▪ Financing and control of the platform ▪ Data protection and confidentiality of third parties ▪ Development of a platform with data interfaces and data restrictions
Science	▪ Further develop and validate calculation bases and performance indicator systems (e.g. life cycle assessment (LCA) methodology) ▪ Flexibility towards products and processes at an early stage ▪ Automate methods for sustainable decision making or support them with software ▪ Conceptual development and continuous evaluation of a decision-making platform ▪ Ensure applicability – even without specific expert knowledge ▪ Promote application-oriented cross-sectional research for holistic development and assessment		
Civil society	▪ Emphasise the importance of the user for the life cycle ▪ Emphasise the remaining economic potential of used batteries ▪ Use of second life applications (stationary storage)		

Table 10: Recommendations for action depending on the platform operator

5.2 Joint roadmap for a pilot project

To further develop the pilot project, implementation steps have been defined in Figure 43 and Figure 44 and assigned to three time horizons.

The implementation steps in the platform are divided into stored standardised calculation methods, compressed and simple visualisation methods, and supply and demand forecasts. In the medium term, prototypical decision platforms are to be implemented and further developed so that a valid and robust platform can be developed. For this purpose, it is necessary to develop central incentive systems for the actors along the product life cycle towards a circular value creation.

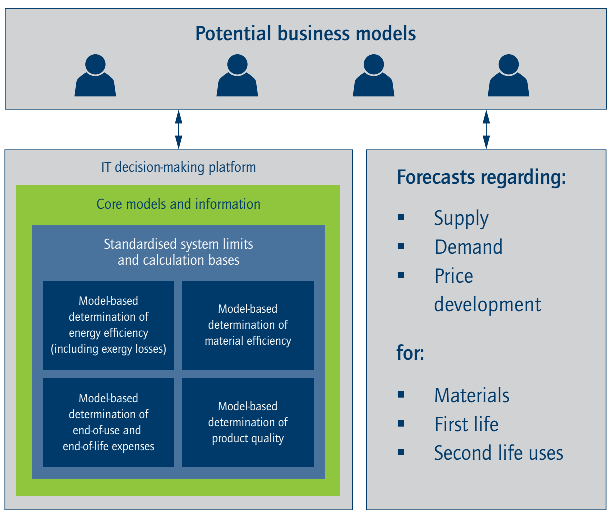

Figure 43: Implementation steps of the model-based decision-making platform (Source: own representation)

Time horizon / Work package	Horizon 1												Horizon 2	Horizon 3
	2021				2022				2023				by 2027	by 2030
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4		
WP1: Development of demand and price forecasts for first- and second-life applications as well as battery materials in Europe by 2035													Identification of possible business models and development of a platform operator; targeted support for a decision-making platform, including financial support for prototyping; development of an incentive system for circular value creation in networks	Completion/further development of models; implementation of the decision-making platform; involvement of other actors
WP2: Definition of international/European calculation standards, system boundaries, and key figures for the assessment of end-of-use/end-of-life scenarios														
WP3: Conceptual development of a platform for different operators														
WP4: Model-based determination of the energy efficiency (including exergy losses) of various process routes														
WP5: Model-based determination of the material efficiency of various process routes														
WP6: Model-based determination of necessary expenditures and achievable product qualities of different end-of-use/end-of-life applications														
WP7: Development of user-friendly, compressed calculation and visualisation methods														
WP8: Development of the roadmap for a decision-making platform for traction batteries in Europe by 2035														

Figure 44: Roadmap of the model-based decision-making platform (Source: own representation)

6 Outlook

For further details and coordination of the pilot project, reference is made to the umbrella concept "Battery Research Factory" of the Federal Ministry of Education and Research (BMBF). With this concept, the BMBF is pursuing a topic-oriented, coherent, national approach to the promotion and further development of battery research in Germany. The initiatives are closely linked with those of the Federal Ministry of Economics and Energy (BMWi) with a view to establishing large-scale battery cell production and covering the entire value chain. In particular, the cross-sectional initiative Battery Life Cycle and the establishment of two new competence clusters are intended to strengthen the implementation of a Circular Economy for mobile energy storage in Germany:

- **Competence cluster "Recycling/Green Battery":** The competence cluster focuses on sustainable battery cell production under the premise of the efficient use of resources. The aim of this priority area is to develop concepts for a battery design that is suitable for recycling. The design is to be realised at the different levels of a battery (material, cell component, and cell level). The (further) development of recycling processes is also intended to address the function-preserving recovery of material from the recycling stream and from residues of the production process.
- **Competence cluster "Battery utilisation concepts":** In the competence cluster, expertise for module or cell diagnosis, including end-of-life rapid characterisation and condition determination, is to be developed. Accelerated ageing procedures and safety concepts are also addressed. The data collected will be used for cell development and production processes. Through this iterative process, they contribute to resource protection. A complementary system and application analysis is proposed for the successful implementation of the module. In addition to monitoring trends in the field of energy storage, it is important to collect and analyse economic, energy, and environmental data.

Costs and potential environmental impacts along the life cycle of batteries are being investigated across clusters. With the aim of a (battery) system evaluation, potential future battery systems are also analysed with regard to their economic efficiency, application relevance, and life cycle assessment.

6.1 Expected challenges

- Central to the intended modelling is a specification of the required data input (e.g. regarding the condition of the battery, future ramp-up rates, market penetration rates). In order to be able to carry out a corresponding scenario assessment, it is necessary to agree on and define certain standards and target systems (e.g. with regard to different second-use application cases).
- A harmonisation of industry standards at the interface between the use cases "mobile power storage" and "stationary power storage" also seems relevant here.

6.2 Open questions and possible next steps

- Certificate trading for secondary raw materials as a possible incentive system
- Influence of substance bans on material flows
- Learning from the primary industry: Consideration of treatment and refining charges (recycling as a service business, metal ownership remains with the vehicle manufacturer or supplier of the recycled batteries)
- Focus of recycling on (certified) output quality
- Definition of guidelines for the allocation, distribution, and documentation of credits through reuse and recycling

Pilot Profile III: "Dismantling network for traction batteries"

1 Motivation and objective

The pilot profile III "Dismantling Network for Traction Batteries" has been agreed and formulated in the course of the work of the "Traction Batteries" working group of the *Circular Economy Initiative Deutschland* with experts from industry and science (see members of the sub-working group in the Project chapter of the General Report). The pilot profile is to be understood as a technically well-founded proposal to the responsible ministries of the Federal Government from the point of view of technical expertise because an important and necessary contribution to the essential optimisation of the recycling management has been identified.

1.1 Current challenges in the system

For the recycling of lithium-ion batteries from electric vehicles, dismantling facilities for the testing, discharging, and disassembling of large lithium-ion batteries (in the case of fully electric cars, these are battery weights of several hundred kilograms) are an important and decisive interface. On one hand, large numbers of batteries can be examined for their suitability for a second life (e.g. as a vehicle replacement battery or as stationary energy storage) (Figure 45). On the other hand, lithium-ion batteries not suitable for secondary life are dismantled in appropriate facilities with suitable infrastructure (e.g. lifting devices, roller tables, cordless screwdrivers, and robots) at the module level or even down to the cell level if necessary.

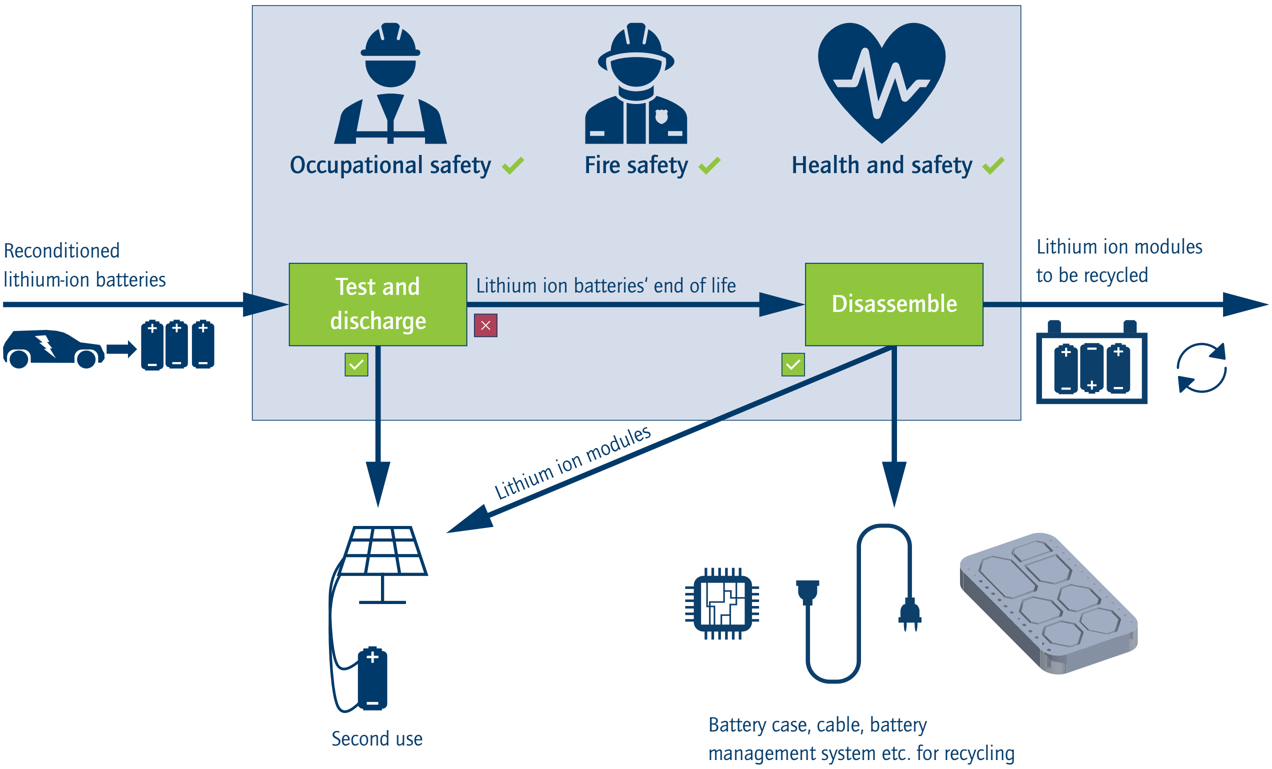

Figure 45: Concept of a dismantling facility for traction batteries (Source: own representation)

The separated peripheral components (e.g. battery casings, screws, cables, battery management system) are important value components that, once separated, can be fed directly into existing recycling circuits. From a series of life cycle assessments on the recycling of corresponding lithium-ion batteries,[248, 249, 250, 251] it is known that recycling these components contributes to a positive overall recycling balance. The dismantled battery modules themselves are either further treated at the site of the dismantling facility (depending on the location of subsequent recycling) or are packaged in accordance with regulations for transport to an external recycling facility. The subsequent recycling of the battery modules is intended to once again provide key materials such as lithium, nickel, and cobalt salts in battery-compatible quality to the European value chain for lithium-ion batteries.

Necessary standards of dismantling facilities

The members of the pilot project III "Dismantling Network for Traction Batteries" agree that, with regard to fire protection, and occupational health and safety, there is still a widespread lack of uniform standards – even within Germany (let alone throughout the EU) – for corresponding dismantling facilities. This also applies to the necessary qualifications of those employed there. It is therefore necessary to coordinate minimum standards for fire protection, and health and occupational safety for dismantling facilities throughout the EU as well as for the necessary professional qualification of the workers employed there (among other things, appropriate courses on safe handling of high-voltage systems are important).

Definition of the spatial dimension for the consideration and solution of problems

In addition to challenges regarding uniform standards and requirements for the dismantling facilities themselves, the spatial-logistical dimension is a further challenge within the European Union in several respects:

- The ramp-up of electromobility will be at different speeds in the various European countries; this means that the accumulation of end-of-life batteries will also be distributed quite differently.
- Until further notice, the recycling facilities for modules from high-voltage batteries will be concentrated in a few EU countries as large, centralised facilities.
- Small quantities of end-of-life batteries and long transport distances will keep logistics costs high for the time being. The future intelligent and optimal localisation and dimensioning of dismantling facilities in Europe will therefore be a decisive step towards professionalising the recycling chain and reducing logistics costs.

Among the participants in this pilot project, there is agreement that Europe-wide solutions for the best possible logistical solution for recycling or second life of lithium-ion batteries from electric vehicles are desirable. This means that:

- It does not make sense to act within national borders; it is also necessary to plan in EU dimensions against the background of possible solutions for the German economy.
- This results in corresponding problems of national peculiarities both with regard to safety standards and further specifications as well as notification procedures for cross-border transport and cross-border logistics.

Definition of the time dimension for the consideration and solution of problems

Among the participants in the pilot project "Dismantling Network for Traction Batteries", there is agreement that this is a classic "chicken and egg" problem with regard to the necessary establishment of a network of dismantling facilities in Europe. As long as there are still few end-of-life batteries of electric vehicles, the incentive for potential operators to set up and operate dismantling facilities is low. On the other hand, a small number of dismantling facilities) in Europe means that because of long transport distances alone (from the removal of the batteries from the vehicles in workshops to the dismantling facilities), the specific logistics costs and thus CO_2 emissions of transport are very high. Because the market ramp-up of electromobility is expected to lead to a considerable increase in the number of end-of-life batteries from electromobility in Europe over the next 10 to 15 years with a corresponding time lag – starting from a currently very low starting level – the major challenge is to design this transition period (until around 2030/2035) as optimally as possible. Investment decisions for new dismantling facilities must be made on a well-founded data basis with regard to timing, choice of location, dimensioning of the facility in line with future growth in return volumes, and the specification of the facility equipment (degree and adaptability of automation regard changing battery formats and chemistries). In this way, the recycling infrastructure can be precisely improved and made scalable on a European level.

248 | See Buchert et al. 2011.
249 | See EcoBatRec 2016.
250 | See LithoREC I 2012.
251 | See LithoREC II 2016.

Dismantling design as a prerequisite for highly automated disassembly

Finally, a further challenge for the operation of recycling facilities consists of a forced dismantling design (design for disassembly) as an essential prerequisite for a future highly automated disassembly. At present – not least because of the high diversity in design and above all the type of housing connections of the high-voltage batteries – time-consuming and labour-intensive, predominantly manual process steps must be carried out in the dismantling facilities in order to realise the disassembly at the module level (and if necessary, down to the cell level).

With a forced design for disassembly, the following advantages are to be tapped for larger volume flows of end-of-life batteries in the future:

- Higher occupational safety and effectiveness
- Cost reductions
- Capacity increases with drastically increasing quantities of end-of-life batteries
- Additional benefits through further developments by industry 4.0[252]

Definition of the pre-competitive area to be jointly organised, need for information transfer and standardisation

- It makes sense to bundle material flows (batteries and/or their components) in order to make transport, storage, and treatment economically efficient. To this end, demarcations must be drawn between individual and cooperative approaches. An essential framework condition would then be the creation of a kind of IDIS[253] (International Dismantling Information System) for batteries with regard to the information released.
- Removal, condition assessment, storage, transport, disassembly, and securing must be uniformly defined and must be credibly and justifiably enforceable – also vis-à-vis insurance companies (fire protection standards) – in order to contain the incidental costs of the processes as well as to be able to provide all handlers along the chain with the necessary information and safety aspects.
- In terms of a design for disassembly, the prerequisites for a highly automated disassembly process for larger future volume flows must be created.

1.2 Focus and definitions of the pilot topic

Within the framework of the planned pilot project “Dismantling Network for Traction Batteries”, concrete proposals for solutions to the following objectives are to be developed in order to meet the challenges listed above:

- detailed formulation of the necessary Europe-wide valid standards for dismantling facilities for lithium-ion batteries (disassembly at the module level and, if necessary, down to the cell level) from electric vehicles: appropriate safety levels (fire prevention and firefighting), occupational health and safety standards (appropriate protective equipment, auxiliary power units), health standards (appropriate air exchange, good air extraction at workplaces), appropriate qualifications of employees (development of the contents of appropriate additional training courses specifically for handling high-voltage batteries from the electric mobility sector)
- Formulation of the specific requirements for a design for disassembly from the perspective of disassembly practice in order to enable more automated disassembly processes in the future
- Development of concrete proposals for an appropriate Europe-wide ramp-up of the number of dismantling facilities and logistics centres by 2035 (definition of minimum capacities, optimum location, cooperation with authorised and independent workshops, examination of whether investment aid (European Investment Bank) is appropriate to ease investment reluctance)

2 Success criteria for the implementation

The following points are success criteria for the realisation of the extensive pilot project “Dismantling Network for Traction Batteries”.

2.1 Overview of actors from the field to be involved

Actors from the following areas are to be involved in the implementation of the pilot project. It should be borne in mind that individual actors may also cover several functions.

252 | Thus, comprehensive digitisation can result in a wide range of benefits such as increased transparency in product tracking (see also Pilot Profile I “Understanding the service life of the battery"), efficiency gains in internal and external processes, or an increase in connectivity with regard to downstream value creation paths (see also Pilot Profile II “Model-based Decision-making Platform").

253 | See IDIS 2020.

1. Actors in material flow
   - Vehicle (parts) manufacturers
   - Contract workshops of the vehicle manufacturers
   - Free workshops
   - Battery component manufacturer
   - Battery or cell manufacturer
   - Car recycler
   - Logisticians
   - Dismantling companies
   - Refurbisher
   - Metallurgical recyclers

2. Stakeholders in the periphery
   - Service (IT, tracing and tracking, monitoring, reporting)
   - Mechanical engineers who provide dismantling devices. This assists the workers during dismantling (e.g. lifting the battery, screwing, opening the system)
   - Testing authority that uses certain criteria to decide on the end-of-life use of the batteries (see also Pilot Profile II "Model-based Decision-making Platform"), insurers (especially with regard to the design of storage and fire protection standards)
   - Scientific institutions with relevant experience in the recycling of lithium-ion batteries
   - Transport box manufacturer

3. Regulatory systems:
   - Authorities for monitoring
   - Authorities for legislation
   - Border control authorities (customs)

For a comprehensive pilot project "Dismantling network for traction batteries", a consortium should be composed of the aforementioned actors. The scope as well as the type and intensity of participation (as a member of the project consortium, subcontractor, member of the European Support Group) would have to be agreed before submitting a concrete project outline.

2.2 Consideration of the relevant need for action with regard to the regulatory framework

Within this pilot project, the following relevant needs for action regarding regulatory framework conditions for a dismantling network for traction batteries were identified. These include the areas of waste law, hazardous goods law, fire protection, occupational health and safety, health protection, and design for disassembly:

- Harmonisation of national (and sub- or supranational) regulations for the classification of lithium-ion batteries as "hazardous" waste;[254, 255]
- Harmonisation of national (and sub- or supra-national) authority interpretations of the cross-border shipment of lithium-ion batteries as (possibly hazardous) waste (via "Amber List/Notification" versus "Green List" according to the Basel Convention);[256, 257]
- Practical and implementable dangerous goods regulations for the transport of critical ("not transport safe") lithium-ion batteries by the nationally responsible authorities (e.g. by the Federal Institute for Materials Research and Testing (BAM) in Germany);[258, 259];
- Technical and administrative solutions for the fast tracking of cross-border transports of certified actors;
- Standards and guidelines for handling and disassembly procedures that influence the design (design for disassembly);
- Occupational safety standards for battery handling and standards for high-quality dismantling processes (occupational safety, health protection, fire protection);
- Legal regulations for the evaluation of battery condition (e.g. accident-related, discharged);
- Development of legal definitions that clarify when a battery is "damaged",
  - There are already standards for this depending on the supplier but no clear distinction (only a distinction in green, yellow, red for the safety of the handling);
- Regulations for the professional determination of the battery condition,
  - Keyword battery testing;
- Regulations on remaining of charge and state of health (SoH) for the decision-making process for second life or recycling

254 | See at EU level: Index of EU Commission Decision No. 2000/532/EC, "European Waste Code".| See Europäische Union 2000.
255 | See at DE level: Index of the Regulation on the European Waste Catalogue (AVV). | See Bundesanzeiger 2001.
256 | See at EU level: Council decision on the control of trans-boundary movements of hazardous wastes and their disposal (Basel Convention) (93/98/EEC)| See EWG/EU 1993.
257 | see Basel Convention on the control of transboundary movements of hazardous wastes and their disposal.| See United Nations Environment Programme 1989.
258 | See European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). | See UNECE 1957.
259 | See Bundesanstalt für Materialforschung und -prüfung 2019.

- (see also the pilot profile II "Model-based decision-making platform");
- Obligatory regulations on the availability of dismantling instructions (in digital structure).

2.3 Qualifications required to implement the pilot project

A project consortium "Dismantling network for traction batteries" should cover the following qualifications through its members:

- Comprehensive experience and knowledge of professional recycling circuits for lithium-ion batteries to recover high-quality battery materials;
- Practical experience in discharging, testing, and evaluating with regard to second life and disassembling lithium-ion batteries from electric vehicles (if possible, existing infrastructure for this purpose);
- Extensive experience and expertise in occupational health and safety requirements for the dismantling of traction batteries and in fire prevention and firefighting infrastructures for the treatment of lithium-ion batteries;
- Comprehensive overview of all relevant regulatory framework conditions as well as experience-based impulses for the optimisation of regulations;
- Experience and expertise to develop differentiated scenarios (taking into account significant differences between the individual EU member states) on the market entry and accumulation of lithium-ion batteries from electric vehicles (total mass flow potential of the batteries, additional key materials such as lithium, nickel, cobalt, and copper).

3 Expected potential of the pilot project

3.1 Impact on the vision 2030

The pilot project "Dismantling Network for Traction Batteries" is intended to make a substantial contribution to the following aspects of the vision 2030 (see Section 3.3 in the General Report)

- Regulatory systems: Uniform international standards regarding the end-of-life treatment and logistics of traction batteries have helped to eliminate unfair competition and dumping.
- Material flows: By 2030, a small (about 10%) but growing share of the demand for key materials for lithium-ion batteries will be met by recycled materials,[260] and the carbon and environmental footprint of the batteries will be improved.
- Technical development: Design for circularity/design for recycling have become the industry standard and enable value network participants to safely and efficiently handle batteries for circular business models throughout the battery life cycle.
- Technical development: The increasing automation of maintenance and dismantling enables the scaling and cost reduction of reuse and end-of-life measures. Nevertheless, the Circular Economy for traction batteries remains a job engine because a great deal of expertise and human intervention remains necessary even in almost fully automated processes.
- Internal implementation: The establishment of effective dismantling networks (dismantling, assessment, and transport) has led to the efficient and safe handling of the rapidly increasing quantities of end-of-life batteries. Early management has led to an efficient combination of decentralised locations for optimised reverse logistics and centralised facilities for economies of scale.

The establishment of a Europe-wide network of efficient dismantling facilities for traction batteries is essential for the success of the entire recycling or reuse chain. After all, it is an important link between collection (e.g. authorised workshops) and the further treatment/recycling (or second life) of the battery modules. The modern, preferably automated disassembly of high-voltage batteries in facilities that meet high fire, occupational health, and safety requirements and which are operated by highly qualified personnel must become an important brand core of the recycling industry in Europe.

3.2 Environmental, social, and economic potentials

The pilot project "Dismantling Network for Traction Batteries" is intended to prepare for the following potential from the recycling of lithium-ion batteries in electric vehicles to be tapped throughout Europe

- Environmental: An efficient network of professionally equipped and operated dismantling centres throughout Europe ensures the optimal allocation of battery storage for a second life or dismantling oriented to target fractions and subsequent high-quality recycling of the components. This will further improve the overall environmental balance of traction batteries and electric vehicles as a whole and open up a sustainable raw material source of key materials for electric mobility in Europe itself.
- Social: By optimising this important module of a recycling management of traction batteries, sustainable jobs with different requirement profiles will be created throughout Europe.
- Business: The pilot project "Dismantling Network for Traction Batteries" is intended to make a significant contribution to

260 | See Buchert et al. 2019.

the optimal development of the value-added chains in this area of the recycling management. Because of optimised test procedures, efficiency potentials are opened up for revenues on the one hand (decision for second-life versus end-of-life per battery system) and costs are reduced on the other hand by optimised dismantling procedures (among other things, by design for dismantling, automated disassembly), the avoidance of fire incidents, and optimised logistics (combination of decentralised and centralised facilities in the most suitable locations).

4 Roadmap for the pilot project Dismantling network for traction batteries

Within the framework of a comprehensive pilot project "Dismantling Network for Traction Batteries", a detailed roadmap for a corresponding dismantling network in Europe is to be developed in the short term in a three-year process. The roadmap is supplemented by medium-term measures with a time horizon up to 2030. In Figure 46, a proposal for the main work packages and their processing is visualised.

Time horizon / Work package	Horizon 1												Horizon 2	Horizon 3
	2021				2022				2023				by 2027	by 2030
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4		
WP1: Scenario-based ramp-up model for disassembly plants in Europe													Building on the standards and roadmaps: Member States and the European Commission (and, where appropriate, the European Investment Bank) provide targeted support to disassembly networks, including financial support, support for prototyping, and regional differentiation	Complete the disassembly network up to a high degree of maturity to be prepared for return flow rates in 2030/2035. In particular, structural support for the southern and eastern EU member states based on modelling requirements
WP2: Occupational health and safety standards for disassembly plants														
WP3: Fire prevention standards and fire fighting standards for disassembly facilities														
WP4: Development of customised additional qualifications for employees in disassembly plants														
WP5: Design for Disassembly for automated disassembly														
WP6: Coordination of all work with a European support group														
WP7: Developing the roadmap for a disassembly network for mobile electricity storage in Europe by 2035														

Figure 46: Possible implementation steps for the establishment of a Europe-wide dismantling network (Source: own representation)

Work package 1: Development and evaluation of a scenario-based ramp-up model for dismantling facilities in Europe until 2035

In this work package, differentiated scenarios on the market entry and the production of lithium-ion batteries from electric vehicles in Europe until 2035 are developed. This must take into account both the different characteristics of the market ramp-up as well as the accumulation of lithium-ion batteries in the individual EU member states for the volume flows and other important variables such as trends in cell composition (lithium, nickel, cobalt). For the question of the necessary location and dimensioning of dismantling facilities in Europe until 2035 ("dismantling network"), interviews with selected actors from the automotive industry, the logistics sector, and the recycling industry will be conducted in order to transfer the volume flows of end-of-life batteries calculated from the scenarios into a run-up model for dismantling facilities in Europe. This work is to be carried out at an early stage of the overall project in order to provide the network partners with important impulses for the other work packages. At the end of the project period, a short review and validation loop of the scenarios will take place in order to incorporate the latest trends and dynamics as required.

Work package 2: Development and coordination of appropriate occupational health and safety standards for dismantling facilities

The development and coordination of appropriate occupational safety standards (health and safety at work) is an essential component of modern dismantling facilities. Because in many regions and member states of the European Union, industrial uncharted territory is being broken with the construction of such facilities, and the risk potential in testing, discharging, and disassembly of the batteries (high-voltage systems, possible hydrogen fluoride emissions) must not be underestimated, uniform standards are to be developed and proposed throughout Europe. Also for the results of this work package, a validation loop towards the end of the project should ensure that the latest findings are incorporated into the work.

Work package 3: Development and coordination of appropriate fire prevention and firefighting standards for dismantling facilities

Fire incidents, some of which cause considerable damage, are an increasing phenomenon in connection with the handling of lithium-ion batteries and an urgent challenge in the recycling industry. The requirements and policies of the insurance industry for operators are increasing accordingly and must be taken into account in the total costs of battery recycling. For this reason, a manual for fire prevention and firefighting standards for dismantling facilities is being developed – not least based on the experience and learning curves of actors in practice. A Europe-wide harmonisation of standards is essential in order to avoid market distortions within Europe.

Work package 4: Elaboration and coordination for precisely fitting additional qualifications of employees in dismantling facilities

Dismantling facilities for lithium-ion batteries from electric vehicles can be operated safely and efficiently only if the personnel in these facilities are optimally trained and educated. In this report, participating experts from the field have already pointed out a number of serious deficits (e.g. lack of customised further training courses); these are to be counteracted in a qualified manner in this work package. The result of this work package is a dedicated catalogue of requirements for the necessary basic vocational qualification and for important additional training that the personnel of corresponding facilities must fulfil depending on their function (e.g. facility manager, cutting worker) in order to meet the relevant requirements.

Work package 5: Design for disassembly automated disassembly

Against the background of a significant increase in the volume of lithium-ion batteries from electric vehicles in Europe over the next 10 to 15 years, more automated disassembly has a high potential for efficiency increases and cost reductions. An important prerequisite for this is that the experiences and requirements of the practical actors for optimal disassembly are translated into impulses for an optimised design for disassembly. The result of this work package is a catalogue of requirements with priorities for a battery design that strongly supports a later automated disassembly of the batteries – without limiting the functionality of the lithium-ion batteries during the usage phase.

Work package 6: Coordination of all work with a European monitoring group

The establishment of an efficient dismantling network is a task with a European dimension because even today – despite even lower volume flows – the recycling flows of high-voltage batteries are already organised transnationally in the European Union. For this reason, the work in this proposed project will be supported by an advisory group consisting of experts from various disciplines (vehicle (parts) manufacturers, recycling companies, regulatory systems, standardisation, service providers) from representatives of the European Commission as well as from different member states. It is important here that the various regional clusters within the EU are well represented. This European support group is to work over almost the entire project duration, receive regular presentations of interim results from the various work packages, and finally make recommendations to the project team on necessary adjustments for the optimal European harmonisation of standards and regulations.

Work package 7: Preparation of the roadmap for a dismantling network for traction batteries in Europe by 2035

Finally, the project consortium will use the results of all work packages to jointly develop an implementation plan for the development of an efficient dismantling network for traction batteries in Europe with a timeline up to 2035. This should flank the ramp-up of electromobility with an appropriate roadmap for a dismantling network. According to the expected return volumes of high-voltage batteries, a phased plan for the expansion of the dismantling network will be drawn up; this will comprise all elements of the work packages outlined above. The roadmap should give clear indications as to when, where, and with what capacities dismantling facilities must be built in Europe by 2035, what investments are needed for this, and what financing methods can be recommended for implementation. The roadmap is to be presented, not least through the contacts of the European Monitoring Group both at member state and EU level (Commission, European Parliament, industry associations), and its implementation in the context of the European Green Deal is to be strongly promoted.

5 Outlook

In accordance with the overarching goals of the European Green Deal of the European Union and the corresponding goals of the German Federal Government, the optimisation of the recycling management branch represents an important set screw for the conservation of resources and for forced climate protection. In particular, optimised recycling (including reuse) of lithium-ion batteries in Europe promises considerable potential in the medium and long term for reducing dependence on non-European sources of raw materials and making an important contribution to resource and climate protection. The adoption of this proposal for a comprehensive pilot project “Dismantling network for traction batteries” is subject to examination and decision by the respective federal ministries.

Bibliography

Abadías Llamas et al. 2020
Abadías Llamas, A./Bartie, N. J./Heibeck, M./Stelter, M./Reuter, M. A.: „Simulation-Based Exergy Analysis of Large Circular Economy Systems: Zinc Production Coupled to CdTe Photovoltaic Module Life Cycle“. In: *Journal of Sustainable Metallurgy*, 6: 1, 2020, p. 34–67.

acatech 2020
acatech: *EIBA. Sensorische Erfassung, automatisierte Identifikation und Bewertung von Altteilen anhand von Produktdaten sowie Informationen über bisherige Lieferungen*, 2020. URL: https://www.acatech.de/projekt/eiba-sensorische-erfassung-automatisierte-identifikation-und-bewertung-von-altteilen-anhand-von-produktdaten-sowie-informationen-ueber-bisherige-lieferungen/ [As of: 30.06.2020].

Agora Verkehrswende 2017
Agora Verkehrswende: *Mit der Verkehrswende die Mobilität von morgen sichern. 12 Thesen zur Verkehrswende*, 2017. URL: https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/12_Thesen/Agora-Verkehrswende-12-Thesen_WEB.pdf [As of: 22.06.2020].

Agora Verkehrswende 2018
Agora Verkehrswende: *Klimaschutz 2030 im Verkehr: Maßnahmen zur Erreichung des Sektorziels*, 2018. URL: https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/Klimaschutzszenarien/Agora_Verkehswende_Klimaschutz_im_Verkehr_Massnahmen_zur_Erreichung_des_Sektorziels_2030.pdf [As of: 22.06.2020].

Agora Verkehrswende 2019
Agora Verkehrswende: *Klimabilanz von Elektroautos. Einflussfaktoren und Verbesserungspotenzial*, 2019. URL: https://www.agora-verkehrswende.de/fileadmin/Projekte/2018/Klimabilanz_von_Elektroautos/Agora-Verkehrswende_22_Klimabilanz-von-Elektroautos_WEB.pdf [As of: 22.06.2020].

Agora Verkehrswende/Agora Energiewende 2018
Agora Verkehrswende/Agora Energiewende: *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe*, 2018. URL: https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/Die_Kosten_synthetischer_Brenn-_und_Kraftstoffe_bis_2050/Agora_SynCost-Studie_WEB.pdf [As of: 30.06.2020].

Ahmadi et al. 2014
Ahmadi, L./Yip, A./Fowler, M./Young, S. B./Fraser, R. A.: „Environmental Feasibility of Re-use of Electric Vehicle Batteries“. In: *Sustainable Energy Technologies and Assessments*, 6, 2014, p. 64–74.

Arbib/Seba 2017
Arbib, J./Seba, T.: *Rethinking Transportation 2020–2030*, 2017.

Ardente et al. 2018
Ardente, F./Talens Peiró, L./Mathieux, F./Polverini, D.: „Accounting for the Environmental Benefits of Remanufactured Products: Method and Application“. In: *Journal of Cleaner Production*, 198, 2018, p. 1545–1558.

Ashby 2016
Ashby, M. F.: *Materials and Sustainable Development*, Butterworth- Heinemann 2016.

Bartie et al. 2020
Bartie, N. J./Abadías Llamas, A./Heibeck, M./Fröhling, M./Volkova, O./Reuter, M. A.: „The Simulation-based Analysis of the Resource Efficiency of the Circular Economy – the Enabling Role of Metallurgical Infrastructure“. In: *Mineral Processing and Extractive Metallurgy*, 129: 2, 2020, p. 229–249.

Bloomberg 2020
Bloomberg: *China Embraces Battery-Swapping System for Electric Vehicles*, 2020. URL: https://www.bloombergquint.com/business/china-embraces-ev-battery-swap-technology-tesla-has-cooled-on [As of: 18.11.2020].

Bobba et al. 2018
Bobba, S./Mathieux, F./Ardente, F./Blengini, G. A./Cusenza, M. A./Podias, A./Pfrang, A.: „Life Cycle Assessment of Repurposed Electric Vehicle Batteries: An Adapted Method Based on Modelling Energy Flows“. In: *Journal of Energy Storage*, 19, 2018, p. 213–225.

Bobba et al. 2019
Bobba, S./Mathieux, F./Blengini, G. A.: „How Will Second-use of Batteries Affect Stocks and Flows in the EU? A Model for Traction Li-ion Batteries“. In: *Resources, Conservation, and Recycling*, 145, 2019, p. 279–291.

Boston Consulting Group/Prognos 2019
Boston Consulting Group/Prognos: *Analyse Klimapfade 2030*, 2019. URL: https://image-src.bcg.com/Images/BCG-Prognos-Analyse-Klimapfade-Verkehr-2030_tcm58-212550.pdf [As of: 22.06.2020].

Buchert et al. 2019
Buchert, M./Dolega, P./Degreif, S.: *Gigafactories für Lithium-Ionen-Zellen – Rohstoffbedarfe für die globale Elektromobilität bis 2050*, Darmstadt 2019.

Buchert et al. 2011
Buchert, M./Jenseit, W./Merz, C./Schüler, D.: *Entwicklung eines realisierbaren Recyclingkonzepts für die Hochleistungsbatterien zukünftiger Elektrofahrzeuge*, LiBRi, Darmstadt 2011.

Bundesanstalt für Materialforschung und -prüfung 2019
Bundesanstalt für Materialforschung und -prüfung: *Damit Lithium-Batterien sicher unterwegs sind*, 2019. URL: https://www.bam.de/Content/DE/Standardartikel/Themen/Energie/damit-lithium-batterien-sicher-unterwegs-sind.html [As of: 30.06.2020].

Bundesanzeiger 2001
Bundesanzeiger: *Verordnung zur Umsetzung des Europäischen Abfallverzeichnisses*, 10.12.2001.

Bundesministerium für Bildung und Forschung 2020
Bundesministerium für Bildung und Forschung: *ReziProK. Ressourceneffiziente Kreislaufwirtschaft – Innovative Produktkreisläufe*, 2020. URL: https://innovative-produktkreislaeufe.de/Verbundprojekte/%C3%9Cbersicht.html [As of: 30.06.2020].

Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2019
Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit: *Referentenentwurf für die Fortschreibung des Deutschen Ressourceneffizienzprogramms ProgRess III*, Berlin 2019. URL: https://www.bmu.de/gesetz/referentenentwurf-fuer-die-fortschreibung-des-deutschen-ressourceneffizienzprogramms-progress-iii/ [As of: 30.06.2020].

Bundesministerium für Wirtschaft und Energie 2017
Bundesministerium für Wirtschaft und Energie: „Tag der Verwaltungsschale: Gelungener Auftakt für den Industrie 4.0-Praxistest“ (Pressemitteilung vom 26.10.2017). URL: https://www.plattform-i40.de/PI40/Redaktion/DE/Kurzmeldungen/2017/2017-09-22_verwaltungsschale.html [As of: 30.06.2020].

Bundesministerium für Wirtschaft und Technologie et al. 2011
Bundesministerium für Wirtschaft und Technologie/Bundesministerium für Verkehr/Bau und Stadtentwicklung/Bundesministerium für Umwelt/Naturschutz und Reaktorsicherheit/ Bundesministerium für Bildung und Forschung: *Regierungsprogramm Elektromobilität*, Berlin, 2011.

Büscher et al. 2017
Büscher, J./Hussy, C./Kessels, K./Koper, M./Munzel, B.: *Support to R&D Strategy for Battery Based Energy Storage* (N° ENER C2/2015-410), 2017.

Bustamante et al. 2020
Bustamante, X./Orfanos, A./Tedesco, R./Zill, M.: *The Positive Side of Batteries*, Brüssel 2020.

Canals Casals et al. 2016
Canals Casals, L./Amante García, B./González Benítez, M. M.: „A Cost Analysis of Electric Vehicle Batteries Second Life Businesses“. In: Ayuso Muñoz, J. L./Yagüe Blanco, J. L./Capuz-Rizo, S. F. (Hrsg.): *Project Management and Engineering Research*, 2014, Cham: Springer International Publishing 2016 (Lecture Notes in Management and Industrial Engineering), p. 129–141.

Cerdas et al. 2018
Cerdas, F./Titscher, P./Bognar, N./Schmuch, R./Winter, M./Kwade, A./Herrmann, C.: „Exploring the Effect of Increased Energy Density on the Environmental Impacts of Traction Batteries: A Comparison of Energy Optimized Lithium-Ion and Lithium-Sulfur Batteries for Mobility Applications“. In: *Energies*, 11: 1, 2018, p. 150.

Ciez/Whitacre 2019
Ciez, R. E./Whitacre, J. F.: „Examining Different Recycling Processes for Lithium-ion Batteries“. In: *Nature Sustainability*, 2: 2, 2019, p. 148–156.

CoreManNEt
CoreManNEt: *Gutschrift*. URL: https://www.coremannet.com/so-funktioniert-coremannet/gutschrift/ [As of: 22.06.2020].

Daimler AG 2014
Daimler AG: *Nachhaltigkeit bei Mercedes Benz PKW*, Stuttgart (unveröffentlicht) 2014.

DIN EN ISO 14040:2009-11 2009
DIN EN ISO 14040:2009-11: *Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen* (ISO 14040:2006), 2009.

Drabik/Rizos 2018
Drabik, E./Rizos, V.: *Prospects for Electric Vehicle Batteries in a Circular Economy* (2018/05), 2018.

EcoBatRec 2016
EcoBatRec: *Demonstrationsanlage für ein kostenneutrales, ressourceneffizientes Processing ausgedienter Li-Ion-Batterien der Elektromobilität*, 2016. URL: https://www.erneuerbar-mobil.de/projekte/ecobatrec [As of: 30.06.2020].

Elektroauto-News 2018
Elektroauto-News: *Fab4Lib – Projekt zum Aufbau einer Großserienfertigung für Lithium-Ionen Batteriezellen gestartet*, 2018. URL: https://www.elektroauto-news.net/2018/fab4lib-projekt-aufbau-grossserienfertigung-lithium-ionen-batteriezellen [As of: 30.06.2020].

elementenergy 2019
elementenergy: *Batteries on Wheels: The Role of Battery Electric Cars in the EU Power System and Beyond*, 2019. URL: https://www.transportenvironment.org/sites/te/files/publications/2019_06_Element_Energy_Batteries_on_wheels_Public_report.pdf [As of: 22.06.2020].

Ellen MacArthur Foundation 2020
Ellen MacArthur Foundation: *Publications*, 2020. URL: https://www.ellenmacarthurfoundation.org/publications [As of: 23.06.2020].

Energy Transitions Commission 2020
Energy Transitions Commission: *7 Priorities to Help the Global Economy Recover. While Building a Healthier, more Resilient, Net-zero Emissions Economy*, 2020.

Europäische Kommission 2019a
Europäische Kommission: *Batteries & Accumulators. Evaluation of the EU Directive 2006/66/EC on Batteries and Accumulators (the Batteries Directive)*, 2019. URL: https://ec.europa.eu/environment/waste/batteries/evaluation.htm [As of: 22.06.2020].

Europäische Kommission 2019b
Europäische Kommission: *Der europäische Grüne Deal*, 2019.

Europäische Kommission 2020
Europäische Kommission: *Eine europäische Datenstrategie*, Brüssel, 2020.

Europäische Union 2000
Europäische Union: 2000/532/EG: *Entscheidung der Kommission vom 3. Mai 2000 zur Ersetzung der Entscheidung 94/3/EG über ein Abfallverzeichnis gemäß Artikel 1 Buchstabe a) der Richtlinie 75/442/EWG des Rates über Abfälle und der Entscheidung 94/904/EG des Rates über ein Verzeichnis gefährlicher Abfälle im Sinne von Artikel 1 Absatz 4 der Richtlinie 91/689/EWG über gefährliche Abfälle (Bekannt gegeben unter Aktenzeichen K(2000) 1147)*, Entscheidung 2000/532/EG 06.09.2000.

Europäische Union 2008
Europäische Union: *Richtlinie 2008/98/EG des Europäischen Parlaments und des Rates vom 19. November 2008 über Abfälle und zur Aufhebung bestimmter Richtlinien*, Richtlinie 2008/98/EG 22.11.2008.

Europäische Union 2009
Europäische Union: *Richtlinie 2009/125/EG des Europäischen Parlaments und des Rates vom 21. Oktober 2009 zur Schaffung eines Rahmens für die Festlegung von Anforderungen an die umweltgerechte Gestaltung energieverbrauchsrelevanter Produkte*, Richtlinie 2009/125/EG 31.10.2009.

Europäische Union 2012
Europäische Union: *Verordnung (EU) Nr. 493/2012 der Kommission vom 11. Juni 2012 mit Durchführungsbestimmungen zur Berechnung der Recyclingeffizienzen von Recyclingverfahren für Altbatterien und Altakkumulatoren gemäß der Richtlinie 2006/66/EG des Europäischen Parlaments und des Rates*, Verordnung (EU) 493/2012 11.06.2012.

Europäische Union 2019
Europäische Union: *Verordnung (EU) Nr. 631/2019 des Europäischen Parlaments und des Rates vom 17. April 2019 zur Festsetzung von CO_2-Emissionsnormen für neue Personenkraftwagen und für neue leichte Nutzfahrzeuge und zur Aufhebung der Verordnungen (EG) Nr. 443/2009 und (EU) Nr. 510/2011*, Verordnung (EU) 631/2019 25.04.2019.

Europäisches Parlament 2020
Europäisches Parlament: „EU COVID-19 Recovery Plan Must be Green and Ambitious, Say MEPs" (Pressemitteilung vom 21.04.2020). URL: https://www.europarl.europa.eu/news/en/press-room/20200419IPR77407/eu-covid-19-recovery-plan-must-be-green-and-ambitious-say-meps [As of: 22.06.2020].

European Investment Bank 2020
European Investment Bank: *The EIB Circular Economy Guide – Supporting the Circular Transition*, 2020. URL: https://www.eib.org/attachments/thematic/circular_economy_guide_en.pdf [As of: 23.06.2020].

EWG/EU 1993
EWG/EU: *Basler Übereinkommen über die Kontrolle der grenzüberschreitenden Verbringung gefährlicher Abfälle und ihrer Entsorgung*, Beschluss 93/98/EWG 1993.

Fritz et al. 2016
Fritz, D./Heinfellner, H./Lichtblau, G./Pölz, W./Schodl, B.: *Ökobilanz alternativer Antriebe. Fokus Elektrofahrzeuge*, Wien: Umweltbundesamt GmbH 2016.

Goldie-Scot 2019
Goldie-Scot, L.: A *Behind the Scenes Take on Lithium-ion Battery Prices*, 2019. URL: https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices [As of: 07.07.2020].

Gsell/Marscheider-Weidemann 2020
Gsell, M./Marscheider-Weidemann, F.: *Second Life von E-Batterien: Potenziale und Marktbarrieren*, 2020.

Hagelüken 2020
Hagelüken, C.: „Business as Unusual. Anforderungen an eine Kreislaufwirtschaft von Lithium-Ionen-Batterien". In: *Müll und Abfall*: 5, 2020, p. 62–80.

Hall et al. 2018
Hall, D./Pavlenko, N./Lutsey, N.: *Beyond Road Vehicles: Survey of Zero-emission Technology Options across the Transport Sector*, 2018.

Hill et al. 2020
Hill, N./Amaral, S./Morgan-Price, S./Nokes, T./Bates, J./Helms, H./Fehrenbach, H./Biemann, K./Abdalla, N./Jöhrens, J./Cotton, E./German, L./Harris, A./Haye, S./Sim, C./Bauen, A.: *Determining the Environmental Impacts of Conventional and Alternatively Fuelled Vehicles through LCA*, 2020. URL: https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1 [As of: 15.08.2020].

Hoekstra/Steinbuch
Hoekstra, A./Steinbuch, M.: *Comparing the Lifetime Green House Gas Emissions of Electric Cars with the Emissions of Cars Using Gasoline or Diesel*. URL: https://www.oliver-krischer.eu/wp-content/uploads/2020/08/English_Studie.pdf [As of: 31.08.2020].

Hoyer 2015
Hoyer, C.: *Strategische Planung des Recyclings von Lithium-Ionen-Batterien aus Elektrofahrzeugen in Deutschland*, Wiesbaden: Springer Fachmedien 2015.

Hüer et al. 2018
Hüer, L./Hagen, S./Thomas, O./Pfisterer, H.-J.: „Impacts of Product- Service Systems on Sustainability – A Structured Literature Review". In: *Procedia CIRP*, 73, 2018, p. 228–234.

IDIS 2020
IDIS: *International Dismantling Information System*, 2020. URL: https://www.idis2.com [As of: 23.06.2020].

International Energy Agency 2019
International Energy Agency: *Global EV Outlook 2019. Scaling up the Transition to Electric Mobility*, 2019. URL: https://www.iea.org/reports/global-ev-outlook-2019 [As of: 23.06.2020].

International Energy Agency 2020
International Energy Agency: *Tracking Transport 2020*, 2020. URL: https://www.iea.org/reports/tracking-transport-2020 [As of: 18.11.2020].

International Resource Panel 2019
International Resource Panel: *Global Resources Outlook. 2019: Natural Resources for the Future We Want*, 2019. URL: https://www.resourcepanel.org/reports/global-resources-outlook [As of: 22.06.2020].

International Resource Panel 2020
International Resource Panel: *Building Resilient Societies After the COVID-19 Pandemic. Key Messages from the International Resource Panel*, 2020. URL: https://www.resourcepanel.org/sites/default/files/documents/document/media/building_resilient_societies_after_the_covid-19_pandemic_-_key_messages_from_the_irp_-_12_may_2020.pdf [As of: 22.06.2020].

IRENA 2019
IRENA: *Innovation outlook: Smart Charging for Electric Vehicles, International Renewable Energy Agency*, 2019. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Innovation_Outlook_EV_smart_charging_2019.pdf [As of: 22.06.2020].

Kampker et al. 2016
Kampker, A./Kreisköther, K./Hollah, A. M./Lienemann, C.: *Electromobile Remanufacturing – Nutzenpotenziale für batterieelektrische Fahrzeuge*, 2016.

Kraftfahrt-Bundesamt 2019a
Kraftfahrt-Bundesamt: *Jahresbilanz des Fahrzeugbestandes am 1. Januar 2019*, 2019. URL: https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/b_jahresbilanz.html [As of: 23.06.2020].

Kraftfahrt-Bundesamt 2019b
Kraftfahrt-Bundesamt: *Verkehr in Kilometern – Inländerfahrleistung*, 2019. URL: https://www.kba.de/DE/Statistik/Kraftverkehr/VerkehrKilometer/vk_inlaenderfahrleistung/vk_inlaenderfahrleistung_inhalt.html?nn=2351536 [As of: 01.07.2020].

Kurdve et al. 2019
Kurdve, M./Zackrisson, M./Johansson, M. I./Ebin, B./Harlin, U.: „Considerations when Modelling EV Battery Circularity Systems". In: *Batteries*, 5: 2, 2019, p. 40.

Kwade/Diekmann 2018
Kwade, A./Diekmann, J.: *Recycling of Lithium-Ion Batteries*, Cham: Springer International Publishing 2018.

Lambert 2017
Lambert, F.: *Tesla is Working on a New Mobile Battery-swap technology to Deploy out of a Trailer*, 2017. URL: https://electrek.co/2017/09/15/tesla-new-battery-swap-technology-to-deploy-trailer/ [As of: 30.60].

Lambert 2020
Lambert, F.: *Nio Might Have Figured out Battery Swap for Electric Cars as it Completes 500,000 Swaps*, 2020. URL: https://electrek.co/2020/06/02/nio-battery-swap-electric-cars-completes-500000-swaps/ [As of: 30.06.2020].

Lebedeva et al. 2018
Lebedeva, N./Tarvydas, D./Tsiropoulos, I.: *Li-ion Batteries for Mobility and Stationary Storage Applications. Scenarios for Costs and Market Growth*, Luxembourg: Publications Office of the European Union 2018.

LithoREC I 2012
LithoREC I: *Recycling von Lithium-Ionen-Batterien*, Braunschweig, 2012.

LithoREC II 2016
LithoREC II: *Recycling von Lithium-Ionen-Batterien – LithoRec II*, Braunschweig, 2016.

Marklines 2017
Marklines: *China's Technology Roadmap: Targets for Energy- saving and New Energy Vehicles in 2030. EVs, PHVs to Account for up to 50% of Vehicle Sales; Focusing on Lightweight Material Development*, 2017. URL: https://www.marklines.com/en/report/rep1558_201612 [As of: 22.06.2020].

Melin 2019a
Melin, H. E.: *Analysis of the Climate Impact of Lithium-ion Batteries and How to Measure It*, 2019. URL: https://www.transportenvironment.org/sites/te/files/publications/2019_11_Analysis_CO2_footprint_lithium-ion_batteries.pdf [As of: 05.08.2020].

Melin 2019b
Melin, H. E.: *State-of-the-art in Reuse and Recycling of Lithium-ion Batteries*, 2019. URL: https://www.energimyndigheten.se/globalassets/forskning–innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf [As of:30.06.2020].

Miedema/Moll 2013
Miedema, J. H./Moll, H. C.: „Lithium Availability in the EU27 for Battery-driven Vehicles: The Impact of Recycling and Substitution on the Confrontation between Supply and Demand until 2050". In: *Resources Policy*, 38: 2, 2013, p. 204–211.

Mohr et al. 2020
Mohr, M./Peters, J. F./Baumann, M./Weil, M.: „Toward a Cell-Chemistry Specific Life Cycle Assessment of Lithium-ion Battery Recycling Processes". In: *Journal of Industrial Ecology*, 2020.

Nationale Plattform Zukunft der Mobilität 2020
Nationale Plattform Zukunft der Mobilität: *Zwischenbericht zur strategischen Personalplanung und -entwicklung im Mobilitätssektor*, Berlin 2020.

Nienaber/Wacket 2020
Nienaber, M./Wacket, M.: „Germany's Merkel Wants Green Recovery from Coronavirus Crisis". In: *Reuters*, 28.04.2020.

OECD 2017
OECD: *Best Available Techniques (BAT) for Preventing and Controlling Industrial Pollution* (OECD Environment, Health and Safety Publications Series on Risk Management 40), 2017.

Ohlendorf 2006
Ohlendorf, M.: *Simulationsgestützte Planung und Bewertung von Demontagesystemen*, Essen: Vulkan-Verl. 2006.

Öko-Institut 2011
Öko-Institut: *Ökobilanz zum „Recycling von Lithium-Ionen- Batterien"* (LithoRec), Darmstadt 2011.

Öko-Institut 2014
Öko-Institut: *eMobil2050. Szenarien zum möglichen Beitrag des elektrischen Verkehrs zum langfristigen Klimaschutz*, 2014. URL: https://www.bmu.de/fileadmin/Daten_BMU/Pools/Forschungsdatenbank/fkz_um_11_96_106_elektromobilitaet_bf.pdf [As of: 30.06.2020].

Öko-Institut 2017
Öko-Institut: *Strategien für die nachhaltige Rohstoffversorgung der Elektromobilität. Synthesepapier zum Rohstoffbedarf für Batterien und Brennstoffzellen. Studie im Auftrag von Agora Verkehrswende*, 2017. URL: https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/Nachhaltige_Rohstoffversorgung_Elektromobilitaet/Agora_Verkehrswende_Synthesenpapier_WEB.pdf [As of: 22.06.2020].

Organisation for Economic Co-operation and Development 2016
Organisation for Economic Co-operation and Development: *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas*, Third Edition, Paris: OECD Publishing 2016.

Outotec
Outotec: *Outotec HSC Chemistry Software*. URL: https://www.outotec.com/products-and-services/technologies/digital-solutions/hsc-chemistry/ [As of: 23.06.2020].

Peters et al. 2017
Peters, J. F./Baumann, M./Zimmermann, B./Braun, J./Weil, M.: „The Environmental Impact of Li-Ion Batteries and the Role of Key Parameters – A Review". In: *Renewable and Sustainable Energy Reviews*, 67, 2017, p. 491–506.

Presse- und Informationsamt der Bundesregierung 2019
Presse- und Informationsamt der Bundesregierung: *Digitalisierung gestalten*, Berlin 2019.

Rauwald 2019
Rauwald, C.: „VW Challenges Rivals With $66 Billion for Electric Car Era". In: *Bloomberg*, 15.11.2019.

Regett 2019
Regett, A.: *Klima- und Ressourcenwirkung von Elektrofahrzeugbatterien: Begleitdokument zum Artikel „Klimabilanz von Elektrofahrzeugen – Ein Plädoyer für mehr Sachlichkeit"*, 2019.

Regett et al. 2019
Regett, A./Mauch, W./Wagner, U.: *Klimabilanz von Elektrofahrzeugen – Ein Plädoyer für mehr Sachlichkeit*, 2019. URL: https://www.ffe.de/attachments/article/856/Klimabilanz_Elektrofahrzeugbatterien_FfE.pdf [As of: 22.06.2020].

Rehme et al. 2016
Rehme, M./Richter, S./Aniko Temmler/Götze, U.: *Second-Life Battery Applications – Market Potentials and Contribution to the Cost Effectiveness of Electric Vehicles*, 2016.

Reuter 2016
Reuter, M. A.: „Digitalizing the Circular Economy". In: *Metallurgical and Materials Transactions B*, 47: 6, 2016, p. 3194–3220.

Reuter et al. 2015
Reuter, M. A./van Schaik, A./Gediga, J.: „Simulation-based Design for Resource Efficiency of Metal Production and Recycling Systems: Cases – Copper Production and Recycling, E-waste (LED lamps) and Nickel Pig iron". In: *The International Journal of Life Cycle Assessment*, 20: 5, 2015, p. 671–693.

Reuter et al. 2019
Reuter, M. A./van Schaik, A./Gutzmer, J./Bartie, N./Abadías- Llamas, A.: „Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective". In: *Annual Review of Materials Research*, 49: 1, 2019, p. 253–274.

Richa et al. 2017a
Richa, K./Babbitt, C. W./Gaustad, G.: „Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy". In: *Journal of Industrial Ecology*, 21: 3, 2017, p. 715–730.

Richa et al. 2017b
Richa, K./Babbitt, C. W./Nenadic, N. G./Gaustad, G.: „Environmental Trade-offs Across Cascading Lithium-ion Battery Life Cycles". In: *The International Journal of Life Cycle Assessment*, 22: 1, 2017, p. 66–81.

Rohr et al. 2017
Rohr, S./Müller, S./Baumann, M./Kerler, M./Ebert, F./Kaden, D./Lienkamp, M.: „Quantifying Uncertainties in Reusing Lithium-ion Batteries from Electric Vehicles". In: *Procedia Manufacturing*, 8, 2017, p. 603–610.

Sachverständigenrat für Umweltfragen 2020
Sachverständigenrat für Umweltfragen: *Umweltgutachten 2020: Für eine entschlossene Umweltpolitik in Deutschland und Europa*, 2020.

Sander et al. 2017a
Sander, K./Gößling-Reisemann, S./Zimmermann, T./Marscheider-Weidemann, F./Wilts, H./Schebeck, L./Wagner, J./Heegn, H./Pehlken, A.: *Recyclingpotenzial strategischer Metalle (ReStra)*, 68, 2017.

Sander et al. 2017b
Sander, K./Sanden, J./Wilts, H.: *Entwicklung von Lösungsvorschlägen, einschließlich rechtlicher Instrumente, zur Verbesserung der Datenlage beim Verbleib von Altfahrzeugen*, 50, Dessau-Roßlau, 2017.

Simon 2019
Simon, F.: „Circular Economy Erected as Number One Priority of European Green Deal". In: *Euractiv*, 13.09.2019.

Steinborn et al. 2010
Steinborn, J./Schmidt, K./Walther, G./Spengler, T. S.: „Integrierte Produktions- und Aufarbeitungsplanung in Unternehmensnetzwerken". In: *uwf UmweltWirtschaftsForum*, 18: 2, 2010, p. 83–89.

Technical Expert Group on Sustainable Finance 2020
Technical Expert Group on Sustainable Finance: *Taxonomy: Final Report of the Technical Expert Group on Sustainable Finance*, 2020. URL: https://ec.europa.eu/knowledge4policy/publication/sustainable-finance-teg-final-report-eu-taxonomy_en [As of: 23.06.2020].

Thielmann et al. 2018
Thielmann, A./Neef, C./Fenske, C./Wietschel, M.: *Energiespeicher Monitoring 2018*, 2018.

Thompson 2018
Thompson, A. W.: „Economic Implications of Lithium Ion Battery Degradation for Vehicle-to-Grid (V2X) Services". In: *Journal of Power Sources*, 396, 2018, p. 691–709.

Transport & Environment 2020
Transport & Environment: *How Clean are Electric Cars? T&E's Analysis of Electric Car Lifecycle CO_2 Emissions*, 2020. URL: https://www.transportenvironment.org/sites/te/files/downloads/T%26E%E2%80%99s%20EV%20life%20cycle%20analysis%20LCA_0.pdf [As of: 15.08.2020].

Umweltbundesamt 2016
Umweltbundesamt: *Altauto, Altautoverwertung*, 2016. URL: https://www.umweltbundesamt.de/umwelttipps-fuer-den-alltag/mobilitaet/altauto-altautoverwertung#unsere-tipps [As of: 10.07.2020].

Umweltbundesamt 2019
Umweltbundesamt: *Verbleib von endgültig außer Betrieb gesetzten Fahrzeugen. Endgültige Außerbetriebsetzungen*, 2019. URL: https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/altfahrzeugverwertung-fahrzeugverbleib#verwertung-der-schredderleichtfraktion [As of: 23.06.2020].

Umweltbundesamt 2020a
Umweltbundesamt: *Energiebedingte Emissionen*, 2020. URL: https://www.umweltbundesamt.de/daten/energie/energiebedingte-emissionen#energiebedingte-treibhausgas-emissionen [As of: 23.06.2020].

Umweltbundesamt 2020b
Umweltbundesamt: *Emissionsquellen*, 2020. URL: https://www.umweltbundesamt.de/themen/klima-energie/treibhausgas-emissionen/emissionsquellen#energie-stationar [As of: 22.06.2020].

UNECE 1957
UNECE: *Europäisches Übereinkommen über die internationale Beförderung gefährlicher Güter auf der Straße*, EDR 1957.

United Nations Environment Programme 1989
United Nations Environment Programme: *Basel Convention*, 1989.

United Nations Human Rights 2011
United Nations Human Rights: *Guiding Principles on Business and Human Rights. Implementing the United Nations "Protect, Respect and Remedy" Framework*, 2011. URL: https://www.ohchr.org/documents/publications/guidingprinciplesbusinesshr_en.pdf [As of: 23.06.2020].

VDI/VDE 2019
VDI/VDE: *Brennstoffzellen- und Batteriefahrzeuge*, 2019.

Verband der Automobilindustrie 2020
Verband der Automobilindustrie: *Export. Jahreszahlen*, 2020. URL: https://www.vda.de/de/services/zahlen-und-daten/jahreszahlen/export.html; https://www.vda.de/de/services/zahlen-und-daten/jahreszahlen/automobilproduktion.html [As of: 23.06.2020].

Weber/Stuchtey 2019
Weber, T./Stuchtey, M.: *Deutschland auf dem Weg zur Circular Economy – Erkenntnisse aus europäischen Strategien (Vorstudie)*, München, 2019.

Wernet et al. 2016
Wernet, G./Bauer, C./Steubing, B./Reinhard, J./Moreno-Ruiz, E./Weidema, B.: „The Ecoinvent Database Version 3 (part I): Overview and Methodology". In: *The International Journal of Life Cycle Assessment*, 21: 9, 2016, p. 1218–1230.

World Economic Forum 2019
Global Battery Alliance: *A Vision for a Sustainable Battery Value Chain in 2030*, 2019.

World Economic Forum 2020
Global Battery Alliance: *The Alliance Brings Together Leading Businesses Along the Entire Battery Value Chain with Governments, International Organizations, NGOs and Academics to Actively Shape a Battery Value Chain that Powers Sustainable Development*, 2020. URL: https://www.weforum.org/global-battery-alliance/action [As of: 22.06.2020].

Worrell/Reuter 2014
Worrell, E./Reuter, M.: *Handbook of Recycling*, Elsevier 2014.

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