EXHIBIT 1016

VEHICLE TECHNOLOGY RESEARCH CENTER FOR LOWER SAXONY

LithoRec
Recycling lithium-ion batteries

Prof. Dr.-Ing. Arno Kwade, Gunnar Bärwaldt (editors)

LithoRec

sponsored by the:

VDI | VDE | IT

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

URT EX1016
URT Umwelt und Recyclingtechnik v. Duesenfeld
IPR2024-00887

Cuvillier Verlag Göttingen
International scientific publisher

www.lithorec.de

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

LithoRec

Recycling lithium-ion batteries

Final report of the joint project

Duration of the project:
September 01, 2009 - September 30, 2011

Joint final report on the following individual projects

16EM0012	I+ME ACTIA GmbH
16EM0013	Audi AG
16EM0014	Electrocycling GmbH
16EM0015	H.C. Starck GmbH
16EM0016	Chemetall GmbH
16EM0017	Westfälische Wilhelms-Universität Münster
16EM0018	Süd-Chemie
16EM0019	Recylex GmbH
16EM0020	Volkswagen AG
16EM0021	Evonik Litarion GmbH
16EM0022	Fränkisches Recycling Zentrum
16EM0023	Brunswick University of Technology

Brunswick, 02.04.2012

VDI|VDE|IT

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Bibliographic information of the German National Library

The German National Library lists this publication in the German National Bibliography; detailed bibliographic data is available on the Internet at http://dnb.d-nb.de.

1st ed. - Göttingen: Cuvillier, 2012

978-3-95404-112-1

© CUVILLIER VERLAG, Göttingen 2012

Nonnenstieg 8, 37075 Göttingen

Tel: 0551-54724-0

Fax: 0551-54724-21

www.cuvillier.de

All rights reserved. It is not permitted to reproduce the book or parts thereof by photomechanical means (photocopy, microcopy) without the express permission of the publisher.

1st Edition, 2012

Printed on acid-free paper

978-3-95404-112-1

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

List of authors

Prof. Arno Kwade (Institute for Particle Technology, TU Brunswick) *Scientific project management*
Gunnar Bärwaldt (Automotive Research Center Niedersachsen) *Project coordination*

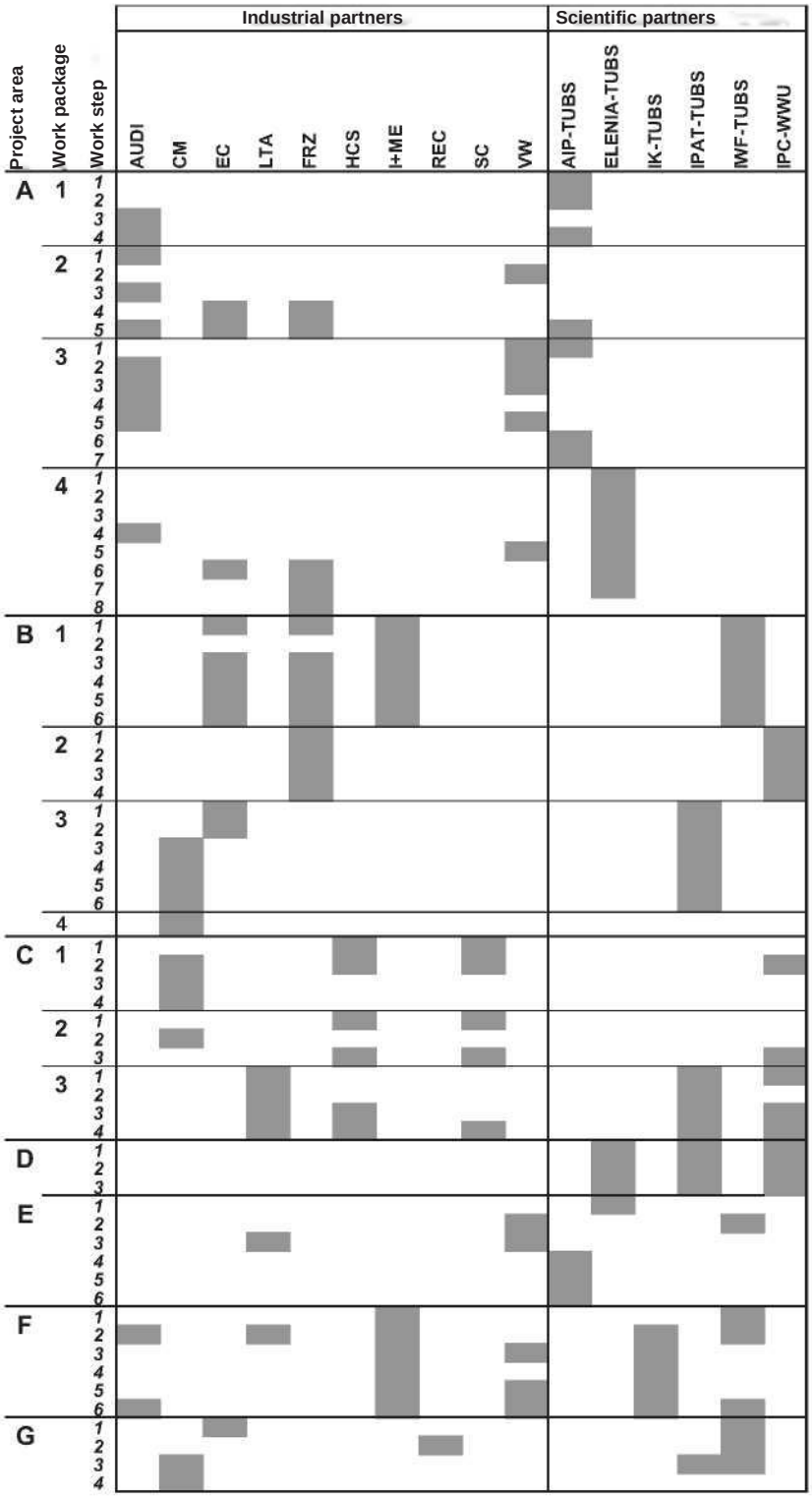
Coordinators of the industrial partners involved
Tobias Meinfelder (AUDI AG)
Martin Steinbild (Chemetall GmbH)
Kai Kramer (Electrocycling GmbH)
Dr. Robert Barenschee (Evonik Litarion GmbH)
Dr. Markus Weinmann (H.C.Starck GmbH)
Axel Schober (I+ME actia GmbH)
Matthias Walch (Fränkisches Recyclingzentrum)
Peter Brandes (Recylex GmbH)
Dr. Nikolas Tran (Süd-Chemie AG)
Dr. Marko Gernuks (Volkswagen AG)

Participating scientific institutions
apl. Prof. Christoph Herrmann, Stefan Andrew
(Institute for Machine Tools and Production Engineering, TU Brunswick)
Prof. Michael Kurrat, Hannes Haupt
(Institute for High Voltage Technology and Electrical Power Systems, TU Brunswick)
Prof. Arno Kwade, Christian Hanisch, Stephan Olliges
(Institute for Particle Technology, TU Brunswick)
Prof. Thomas Spengler, Claas Hoyer
(Institute of Automotive Economics and Industrial Production, TU Brunswick)
Prof. Thomas Vietor, Dennis Wedler
(Institute for Construction Technology, TU Brunswick)
Prof. Martin Winter, Dr. Sascha Nowak
(Institute for Physical Chemistry, WWU Münster)

General contact address:
Brunswick University of Technology
Automotive Research Center of Lower Saxony
Langer Kamp 19
38106 Brunswick
0531-391 7980
nff@tu-braunschweig.de.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Overview of the partners involved in the individual project areas:



The partners involved are responsible for the results and statements within the individual work steps.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

I Table of contents

I Table of contents I
II List of illustrations V
III List of tables IX
A 1 Executive summary 1
A.1 Key results in the individual project areas 2
A.1.1 Project area A 2
A.1.2 Project area B 2
A.1.3 Project area C 3
A.1.4 Project area D 4
A.1.5 Project area E 4
A.1.6 Project area F 4
A.1.7 Project area G 5
A.2 Publications 5
A.3 Definitions 7
A Analysis and development of logistical collection and Feedback processes 8
A.1 Analysis of the volume of used batteries 8
A.1.1 Identification and analysis of the influencing factors relevant to the reflux of used Li-ion batteries 8
A.1.2 Development of a simulation model for estimating the reflux of used Li-ion batteries 9
A.1.2.1 Description of the modules 10
A.1.3 Development of scenarios for the long-term development of sales and use of electric vehicles over time 11
A.1.3.1 Background assumptions 11
A.1.3.2 Scenario assumptions 11
A.1.4 Performing a simulation study on waste battery returns with explicit consideration of uncertain influences 13
A.1.4.1 “Pessimistic” scenario 13
A.1.4.2 “Political” scenario 14
A.1.4.3 “Realistic” scenario 14
A.1.4.4 Comparison of the scenarios 14
A.1.4.5 Sensitivity analysis 17
A.2 Analysis and design of information flows 19
A.2.1 Analysis and adaptation of the information supply and requirements for the expansion and testing processes 19
A.2.2 Analysis and adaptation of information supply and demand for the transportation process 21
A.2.3 Analysis and adaptation of information supply and demand for the storage/collection process 23
A.2.4 Identification of information from upstream processes that is required during the recycling process 25
A.2.5 Design of a tool for the needs-based collection and provision of information and a concept for implementing the tool in a software solution 26
A.2.5.1 Information flow along the process chain 26
A.2.5.2 Options for collecting and providing information in line with requirements 26
A.2.5.3 Requirements for an information tool 28
A.2.5.4 Selection and structure of a suitable information tool 28
A.3 Development of collection concepts 31
A.3.1 Requirements analysis for potential networks for recycling Li-ion batteries 31
A.3.1.1 Definition of system boundaries 31
A.3.1.2 Determining network constellations 34

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A.3.1.3 Derivation of a catalog of requirements ... 37
A.3.2 Development and construction of prototype tools and design of various battery expansion concepts with the help of corresponding expansion studies ... 38
A.3.3 Development and implementation of a packaging system and design of a fastening system ... 40
A.3.4 Development and implementation of a storage system and design of a warehouse ... 42
A.3.5 Economic efficiency calculation of the entire collection concept ... 43
A.3.6 Development of a decision support tool for the design of networks ... 45
A.3.6.1 Modeling the geographical area ... 45
A.3.6.2 Modeling the volume of used batteries ... 46
A.3.6.3 Modeling the processes ... 46
A.3.6.4 Modeling of capacities ... 48
A.3.6.5 Modeling of material flows ... 48
A.3.7 Deriving recommendations for action to design the network structure ... 49
A.3.7.1 Political/VW-OTLG case study ... 50
A.3.7.2 Realistic/VW-OTLG case study ... 53
A.3.7.3 Realistic/VG-10 case study ... 54
A.3.7.4 Robust/VW-OTLG case study ... 55
A.3.7.5 Deriving recommendations for action ... 56
A.4 Development of discharge processes for Li-ion batteries ... 59
A.4.1 Researching secondary markets for lithium-ion battery modules ... 59
A.4.2 Preparation of technical specifications for the secondary markets ... 59
A.4.3 Analysis of existing battery modules with regard to the depth of repair ... 60
A.4.4 Development of an evaluation methodology for battery modules and single cells ... 62
A.4.5 Technical development of a semi-automated test procedure ... 63
A.4.6 Process development for the end loading tool ... 64
A.4.7 Technical development of a semi-automated end loading tool ... 65
A.4.8 Testing the prototype ... 66
B.1 Mechanical dismantling into individual components ... 67
B.1.1 Product analysis and structuring of dismantling ... 67
B.1.2. Concepts for semi-automated dismantling steps ... 71
B.1.3 Design of alternative dismantling systems (layout, linking of workstations/workplaces) ... 77
B.1.4 Design of the elements of the dismantling system ... 85
B.1.6 Derivation of requirements for a battery design suitable for dismantling and automation ... 94
B.2 Treatment and utilization of electrolytes ... 96
B.2.1 Development of opening concepts ... 96
B.2.2 Draining the wet battery cell ... 97
B.2.3 Process development of a suitable distillation process for electrolyte recovery ... 98
B.2.4 Process development of alkaline recrystallization of the conductive salts ... 99
B.3 Mechanical, thermal and chemical processing of the individual components ... 99
B.3.1 Dismantling the dry cells and sorting ... 99
B.3.2 Processing and recycling of cell housings, separators and metallic components ... 100
B.3.3 Process development for the dry separation of active materials from the current collector ... 101
B.3.4 Process development of the wet mechanical separation of the electrode coatings from the current collector and their mechanical separation ... 105
B.3.5 Preparation of highly concentrated, particulate active material suspensions ... 108
B.3.6 Extraction of binder systems from electrode materials depending on the separation alternatives ... 110
B.4 Hydrometallurgical processing and recycling of non-ferrous metals ... 110
B.4.1 Laboratory work on hydrometallurgical extraction and purification processes ... 111

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

B.4.2 Pilot plant for acid-based extractions and fluorine-free conductive salt production ... 120
B.4.3 Pilot plant for purification using ion exchangers and salt splitting using electrodialysis .. 124
C Development of manufacturing processes for “recycling batteries” ... 132
C.1 Characterization of the recycled raw materials ... 133
C.1.1 Creation of a raw material specification for the recycled lithium raw materials by the active material manufacturers ... 133
C.1.2 Evaluation of recycled lithium and transition metal salts in comparison with commercial and recycled primary raw materials ... 135
C.1.3 Comprehensive analysis of chemical and physical material parameters and assessment of potential reuse ... 136
C.1.4 Evaluation of possible uses for different qualities of recovered raw materials ... 136
C.2 Synthesis and characterization of recycled active materials ... 137
C.2.1 Synthesis of active materials from recycled raw materials ... 137
C.2.2 Production of conducting salts from laboratory recycled materials and comparison with commercial conducting salts ... 139
C.2.3 Characterization of active materials - product output control ... 139
C.3 Production and characterization of new electrodes and test cells from recycled active materials ... 143
C.3.1 Standardized electrode and cell production from commercial reference materials and electrochemical characterization ... 143
C.3.2 Standardized electrode and cell production from reconditioned active materials and electrochemical characterization ... 146
C.3.3 Standardized electrode and cell production from recycled active materials obtained from formed cells and electrochemical characterization ... 148
C.3.4 Standardized electrode and cell production from recycled active materials obtained from aged cells and electrochemical characterization ... 150
D.1 Recording the performance and analyzing the aging of conventionally available active materials using a standard cell (LiFePO4 and layered oxides) ... 155
D.2 Recording the performance and analyzing the aging of recycled active materials and multiple recycled active materials using a standard cell (LiFePO4 and layered oxides) ... 167
D.3 Analysis of the mechanisms of ageing in comparison of conventional and recycled active materials ... 174
E Economic and ecological evaluation of recycling concepts for Li-ion batteries ... 174
E.1 Survey and process simulation of energy demand ... 174
E.2 Life cycle assessment of the entire recycling process chain ... 176
E.4 - E.6 Economic evaluation of the LithoRec process ... 176
E.4.1 Modularization and creation of reference systems ... 178
E.4.2 Estimate of investments and fixed costs ... 179
E.4.2.1 Transshipment warehouse ... 179
E.4.2.2 Dismantling plant ... 182
E.4.2.3 Mechanical processing plant ... 184
E.4.2.4 Hydrometallurgical processing plant ... 185
E.4.3 Estimate of process coverage contributions ... 186
E.4.3.1 Definitions and procedure ... 186
E.4.3.2 Contribution margin in dismantling ... 188
E.4.3.3 Contribution margin in mechanical processing ... 190
E.4.3.4 Contribution margin in hydrometallurgical processing ... 192
E.4.3.5 Total process contribution margin and sensitivity analysis ... 193
E.4.4 Break-even points ... 197
E.4.4.1 Throughput-related profit thresholds ... 198
E.4.4.2 Time-related profit thresholds ... 204

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

E. 4.5 Summary 205
F Development of easy-to-disassemble battery systems and life cycle-oriented safety concepts 207
F.1 Development of a tool for integrated recycling and environmental assessment of battery systems 207
F.2 Characteristic dismantling, recycling parameters and dismantling-friendly electrode design 210
F.2.1 Determination of a characteristic dismantling and determination of recycling parameters for representative battery construction concepts 210
F.2.2 Determining a design for electrodes that is easy to dismantle 212
F.3 Development of design and construction guidelines for the dismantling-friendly development/production of batteries 212
F.4 Development of tools (CAD tools, K. catalogs...) for the design and simulation of overall battery concepts, taking into account the mutual influences of battery, peripherals and vehicle technology 216
F.5 Derivation of life cycle-oriented safety concepts, especially for dismantling, dismantling and recycling of lithium-ion batteries 218
F.6 Development of (minimum) documentation standards for proper treatment, dismantling, dismantling and recycling 220
G Conceptual design of a recycling pilot plant 222
G.1 Discharging the batteries and dismantling the system components 223
G.2 Separation of active materials 224
H Bibliography 236
I Annexes 238

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

II List of illustrations

Figure A-1: Concept of the model for estimating the volume of used batteries 9
Figure A-2: Comparison of the used battery volume (mass) of the three scenarios 15
Figure A-3: Comparison of used battery volumes (mass) by battery variant in the three scenarios 16
Figure A-4: Influence of selected parameters on the volume of used batteries 18
Figure A-5: Influence of battery service life on the volume of used batteries (kg/a) 19
Figure A-6: Schematic representation of the recycling information system 30
Figure A-7: Network constellation A - single-level collection concept 35
Figure A-8: Network constellation B - two-stage collection concept with integrated dismantling and processing 36
Figure A-9: Network constellation C - two-stage collection concept with decoupled dismantling and processing 37
Figure A-10: HV - Battery removal KIT 39
Figure A-11: Disposable cardboard packaging Sanyo battery system for Audi Q5 40
Figure A-12: Battery box (battery box made of rigid plastic) 41
Figure A-13: Labeling of warehouse entrances and exits 43
Figure A-14: Module formation from processes 47
Figure A-15: decentralized collection in the “Political/VW-OTLG” case study, second planning period 2015 to the end of 2017 51
Figure A-16: decentralized collection in the “Political/VW-OTLG” case study, third planning period 2018 to the end of 2020 52
Figure A-17: Highly decentralized collection and dismantling in the “Political/VW-OTLG” case study, fourth planning period 2021 to the end of 2025 53
Figure A-18: decentralized collection and dismantling in the “Realistic/VW-OTLG” case study from 2021 to the end of 2025 54
Figure A-19: Comparison of the structures in period III from the case studies “Realistic/VW-OTLG” (a) and “Political/VW-OTLG” (b) with those from the case study “Robust/VW-OTLG” (c) 56
Figure A-20: Comparison of the structures in period IV from the case studies “Realistic/VW-OTLG” (a) and “Political/VW-OTLG” (b) with those from the case study “Robust/VW-OTLG” (c) 56
Figure A-21: Secondary markets 59
Figure A-23: Schematic diagram of the discharging process for battery systems 64
Figure A-24: Current cell discharge and gripper solution 65
Figure A-25: Discharging tool circuit diagram principle 66
Figure A-26: Cell voltage curve during discharge 66
Figure B-1: Impressions of the test dismantling of battery system A 68
Figure B-2: Impressions of the test dismantling of battery system B 68
Figure B-3: Connection graph 69
Figure B-4: Dismantling priority graph 70
Figure B-5: Example assessment of automation capability 72
Figure B-6: Example evaluation of dismantling 72
Figure B-7: Criteria catalog (English) 73
Figure B-8: Portfolio representation for assessing the automation capability for the individual step 74
Figure B-9: Principle of the gripping device (left); parameters for motor design (top right) and control architecture (bottom right) 77
Figure B-10: Schematic of the general dismantling of battery systems 79
Figure B-11: Layout of a dismantling system for the “2015 realistic” scenario 82

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure B-12: Layout of a dismantling system for the “2030 realistic” scenario 84
Figure B-13: Multi-DIAG diagnostic device..... 86
Figure B-14: Gripper system with individual subsystems and components 87
Figure B-15: Operating concept of the gripper system 89
Figure B-16: Screenshots of the visualization 89
Figure B-17: Evaluation of the measurements 93
Figure B-18: Electrode stack (IPC-WWU) 97
Figure B-19: Analysis of the 1st fraction of the distillation process using GC-MS (IPC-WWU) 98
Figure B-20: Analysis of the 2nd fraction of the distillation process using GC-MS (IPC-WWU)99
Figure B-21: Process flow diagram of dry separation 102
Figure B-22: Mechanical separation in the granulator 103
Figure B-23: Proportion of fine fractions after loading in granulators at varying rotor speeds for classification (screening) with different separation particle sizes (6-disc rotor, 2 mm trapezoidal perforated screen) 103
Figure B-24: Process flow diagram wet chemical separation of the coating of battery electrodes 106
Figure B-25: Recycling rate over number of batch dissolving processes..... 106
Figure B-26: Batch filtration operating mechanism (top), operating mode with solvent circuit (bottom) 107
Figure B-27: Process flow diagram of process alternatives for wet chemical separation of the coating of battery electrodes 107
Figure B-28: Particle size distribution of the recovered coating after deagglomeration in impact mill 109
Figure B-29: Concentration and further processing after wet-chemical separation..... 109
Figure B-30: Project scheme for hydrometallurgical battery material recycling..... 111
Figure B-31: Main process components..... 121
Figure B-32: Solids handling 122
Figure B-33: Functionality of an electrolysis with monopolar membrane 125
Figure B-34: Functionality of electrodialysis with bipolar membrane 126
Figure B-35: Original and improved process concept..... 127
Figure B-36: EDBM system..... 129
Figure B-37: Saline solution treatment 130
Figure C-1: Changed recycling cycle 132
Figure C-2: SEM images of the precursors from recycled solutions at 200x, 1000x and 5000x magnification 140
Figure C-3: SEM images of the reference material and the LNCAO materials from recycled solutions at 200x, 1,000x and 5,000x magnification. 141
Figure C-4: Cycling curve of LiFePO4 at room temperature..... 144
Figure C-5: DC rate test of $LiBF_4$ in EC/DMC..... 144
Figure C-6: Electrochemical cycle test of a reference cell made of new materials - current stability test (cycles 1-30) and cycle stability at 3C (cycles 30-500)..... 145
Figure C-7: Electrochemical cycle test of a reference cell made of new materials - characterization of current stability at varying charge rate..... 146
Figure C-8: Electrochemical capacitance curves of reference and cyclized materials 146
Figure C-9: Current carrying capacity test of reconditioned materials 147
Figure C-10: Secondary electron micrographs of the surface of reconditioned electrodes, angle 60°(Source: IPC-WWU and iPAT-TUBS) 147
Figure C-12: CV test 149
Figure C-13: C-rate test V21 and reference 150
Figure C-14: Performance V21 and reference 150
Figure C-15: XRD measurements..... 152

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure C-16: View of the primary particles in the reference (left) and heavy contamination (right) 152
Figure C-17: CV data of all three materials 153
Figure C-18: Cycle stability 153
Figure C-19: C-rate test V5-Z and reference 154
Figure C-20: V5-Z Performance and Reference 154
Figure D-1: Cycling curve of LiFePO4 at 40°C 156
Figure D-2: Cycling curve of NMC at 40°C 156
Figure D-3: Temperature matrix 1CCC with LiBF4 in EC/DMC 157
Figure D-4: Temperature matrix 3CCC with LiBF4 EC/DMC 157
Figure D-5: Discharge of the standard cells to be characterized 158
Figure D-6: Charge of the standard cells to be characterized 158
Figure D-7: Step response of the total voltage of the system 159
Figure D-8: Step response of the single cell voltages 159
Figure D-9: Cell voltage curve during cyclization 161
Figure D-10: Performance of standard layered oxide cells at 1C charge rate 162
Figure D-11: Performance of standard layered oxide cells at 3C charge rate 163
Figure D-12: C rate test at different temperatures 163
Figure D-13: Adhesive force measurement on cyclized cells (standard) 165
Figure D-14: Nanoindentation measurements on NMC standard material 166
Figure D-15: SEM images of NMC standard material 167
Figure D-16: C rate test NMC at 21°C 169
Figure D-17: C rate test NMC at 45°C 169
Figure D-18: Performance NMC at 21°C and 3C 170
Figure D-19: Performance test NMC at 45°C and 3C 170
Figure D-20: Adhesive strength test of NMC material at different loading rates and temperatures 171
Figure D-21: SEM images of NMC recycling material at 1C charge rate 172
Figure D-22: Nanoindentation of recycled material. Charge rate 3C, temperature 21°C 173
Figure D-23: Nanoindentation of recycled material. Charging rate 3C, temperature 45°C 173
Figure E-1: Energy content of the returning battery systems 175
Figure E-2: LithoRec process chain with alternative process paths 177
Figure E-3: Mass composition of the battery mixture used as a basis [t system] 187
Figure E-4: Material flow-related contribution margin in dismantling 188
Figure E-5: Process contribution margin in dismantling 190
Figure E-6: Material and energy flow-related contribution margin in mechanical processing 191
Figure E-7: Process contribution margin in mechanical processing 192
Figure E-8: Contribution margin in hydrometallurgical processing for NMC and LFP systems 193
Figure E-9: Sensitivity analysis regarding process coverage contributions (K-NMC) 195
Figure E-10: Sensitivity analysis regarding process coverage contributions (G-NMC) 196
Figure E-11: Sensitivity analysis regarding process coverage contributions (K-LFP) 196
Figure E-12: Sensitivity analysis regarding process coverage contributions (G-LFP) 196
Figure E-13: Relative deviations of the scenarios from the reference GDB 197
Figure E-14: Profit threshold diagram for hydrometallurgical reprocessing with different compositions of used batteries 199
Figure E-15: Break-even diagram of the overall process for NMC systems 200
Figure E-16: Break-even diagram of the overall process for LFP systems 201
Figure E-17: Break-even diagram of the overall process for mixed volumes 202
Figure E-18: Annual result as a function of throughput and composition of the used battery volume 203

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure E-19: Break-even points depending on the scenarios and percentage deviation of the extreme scenarios from the reference scenario 204
Figure E-20: Time-related break-even points of the individual processes depending on the scenarios for used battery volumes..... 205
Figure E-21: Time-related break-even points of the overall processes depending on the scenarios for used battery volumes..... 205
Figure F-1: Model input in ProdTect using the example of a Li-ion battery..... 208
Figure F-2: Extension of the recycling database in ProdTect 209
Figure F-3: ProdTect result visualization..... 209
Figure F-4: Complete battery system with all necessary components..... 214
Figure F-5: Structure of a design catalog 216
Figure F-6: Example of the valuation option..... 221
Figure F-7: Examples of feasibility in IDIS..... 222
Figure G-1: Mechanical treatment process flow chart 230
Figure G-2: Layout of the processing plant for lithium-ion batteries..... 232
Figure G-3: Sankey diagram of the material flow in the processes..... 233

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

III List of tables

Table A-1: Description of the assumptions of the market and technology development scenarios 12
Table A-2: Scenario parameterization, market development drive concept (A1 - A5) 12
Table A-3: Scenario parameterization, ratio of battery variants used (C1) 12
Table A-4: Scenario parameterization, service life of the batteries by drive concept (C3) 13
Table A-5: Scenario parameterization, re-use/re-use outside the system (D1 and D2) 13
Table A-6: Parameters examined in the sensitivity analysis and their possible characteristics 17
Table A-7: Qualification levels for work on vehicles with high-voltage components 19
Table A-8: Qualifications required depending on activity and hazard potential 20
Table A-9: Recommendations for regulations to be made 21
Table A-10: List of trade association regulations/occupational health and safety regulations .. 24
..... 35
Table A-11: List of requirements at network and process level and possible stakeholders 37
Structural storage requirements: 42
Table A-12: Comparison of net present values in scenario-specific and robust optimization ... 56
Table A-13: Applications in secondary markets 59
Table A-14: Cell parameters 60
Table A-15: Suitability of the battery system for the identified applications 60
Table A-16: Depth of repair battery system A 61
Table A-17: Depth of repair battery system B 61
Table A-18: Repair depth of battery system C 62
Table A-19: Battery characteristics 64
Table B-1: Documentation of dismantling processes (example) 68
Table B-2: Compilation of concepts for handling a battery system from the delivery point to the dismantling site 75
Table B-3: Extract from the list of requirements for the gripping device 76
Table B-4: Return quantities of battery systems (number of units) for the “2015 realistic” and “2030 realistic” scenarios 80
Table B-5: Morphological box of the dismantling systems for the “2015 realistic” scenario 81
Table B-6: Morphological box of the dismantling systems for the “2030 realistic” scenario 83
Table B-7: Return quantities of battery systems (number of units) for the “2030 political” scenario 84
Table B-8: Fractions after dismantling the batteries 92
Table C-1: Specifications of the NiSO4/CoSO4 solutions for LNCAO (left) and LNMCO (right) 133
Table C-2: Specifications for LiOH*H2O 134
Table C-3: Specifications for Li_2CO_3 134
Table C-5: Concentrations and pH values of the solutions of LNCMO V21 vs. LNCMO V5-Z135
Table C-6: Simulation of the solutions (metal salt in g/l solution) 138
Table C-7: Simulation of the solutions for the exact one-third mix with Ni:Co:Mn = 1:1:1 138
Table C-8: Chemical composition of the active materials [mass%] 141
Table C-9: Charge and final charge capacities of two cells each of the reference LNCMO and V21 resp. V5-Z 142
Table C-10: Chemical, physical and electrochemical properties of LiFePO4 materials produced from secondary Li raw materials 142
Table C-11: Comparison of the composition of the reaction solution of V5-Z from the original (small-scale) experiment and the third synthesis cycle 150

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Table D-1: Matrix of ageing tests 156
Table E-1: Typical capacities of automotive battery systems 174
Table E-2: Determined energy consumption 175
Table E-3: Functional units [t systems] and [BEV eq.] and conversion to PHEV and HEV systems 188
Table E-4: Calculation of labor costs 189
Table E-5: Labor costs in mechanical processing 191
Table E-6: Composition of the transition metal salt solution 193
Table E-7: Case distinctions and total process coverage contributions 194
Table E-8: Throughput-related break-even points for all individual processes and the overall process 199
Table F-1: different options for housing division 210
Table F-2: Concepts of easy-to-dismantle battery module design 215
Table F-3: Representation for implementation in CAD 217
Table F-4: Minimum number of modules 218
Table F-5: Different reference options 219
Table G-1: Calculation of requirements for cutting and unloading stations 224
Table G-2: Average composition of lithium-ion battery cells 225
Table G-3: Distribution of significant mass flows for the preparation of 700 kg of cell mass per hour 225
Table G-4: Estimate of the required dedusting air volumes 229
Table G-5: Calculation of the storage requirements for the battery types 233
Table G-6: Estimate of storage space requirements for the products 234
Table G-7: List of machinery and equipment 234

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A 1 Executive summary

In the “LithoRec - Recycling of lithium-ion batteries” project, several processes for recycling traction batteries were evaluated. The planning of the dismantling of the battery systems in LithoRec included not only the pure system planning but also initial investigations into the automation of the dismantling steps, including the prototypical realization of a gripper system for removing battery cells. Processes for disassembling the cells and separating the active materials from the metal foils were established and investigated in the laboratory and also on a pilot plant scale with regard to shredding the cells. A pilot plant was realized in LithoRec for the hydrometallurgical processing of separated coating powder from lithium-ion batteries. Ecological and economic balances based on tests performed on a laboratory or pilot plant scale showed positive results. A conclusive concept was developed for separating the battery systems down to the level of the cathodic active material powder used, which showed very good results in laboratory apparatus.

Most conventional battery recycling processes focus on the recovery of the valuable metals cobalt and nickel using an essentially pyrometallurgical process, which must be combined with hydrometallurgical processes to recover the lithium. The recovery of a significant proportion of lithium is only possible with these processes at an extremely high cost. In LithoRec, on the other hand, a process has been developed in which 85 to over 95%* of the lithium can be recovered by mechanical and hydrometallurgical means, depending on the active material. Another advantage of the “LithoRec process” is that the recovered materials have been proven to be of battery quality when mechanically processed on a laboratory scale, thus creating a closed cycle for strategically important battery raw materials. Lithium hydroxide was precipitated from lithium iron phosphate and new battery-grade NCM was produced from lithium nickel manganese cobalt oxide (NCM).

The automation of the dismantling of lithium-ion battery systems was also investigated theoretically in LithoRec. It was shown that individual dedicated dismantling steps, such as the removal of battery cells, have a high potential for automation. Furthermore, a gripper for cell handling with integrated status determination (voltage measurement and internal resistance determination) was developed as an example. However, due to the environmental conditions in dismantling factories, the wide range of variants or lack of standardization of the systems and the qualification requirements, end-to-end automation of dismantling sequences for battery systems is only feasible to a limited extent, even in the long term.

During mechanical dismantling, in particular the comminution of battery systems, cells and electrodes, impurities occur in the recovered active materials - depending on the processing method - which can cause problems in the synthesis of new active materials. For example, LithoRec revealed process difficulties in the synthesis of LNCMO from solutions deliberately contaminated with significant amounts of aluminum: The aluminum hydroxide co-precipitated in the hydrometallurgical process during transition metal separation led to the spherical transition metal hydroxide particles sticking together, which were highly aggregated after calcination and could no longer be ground up without destructive the previously adjusted morphology. In addition, a contamination-related change in particle morphology was recorded after re-precipitation from contaminated transition metal salt solutions.

* related to separated cathode material as raw material for hydrometallurgical recycling

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Furthermore, new approaches to electrolyte recovery (solvent and conducting salt) were identified in LithoRec. Initial successes have been achieved by means of vacuum condensation and extraction using supercritical carbon dioxide on a very small laboratory scale.

Initial ecological assessments provide an overview of the entire process chain (cradle-to-grave) with a focus on lithium-ion batteries. As part of the two recently completed BMU-funded projects LIBRI and LithoRec, the recycling technologies for lithium-ion batteries were ecologically evaluated. Furthermore, the potential economic viability of recycling large quantities of used batteries in LithoRec was demonstrated.

A.1 Key results in the individual project areas

The main results from the individual project areas are presented below in bullet points. A detailed discussion is provided in the respective work steps.

A.1.1 Project area A

- If the target set by the National Development Plan for Electric Mobility of one million electric vehicles in Germany by 2020 is achieved, 11,000 tonnes of used batteries will already have to be processed in the same year (“Political” scenario). It is assumed that the rapid market penetration will only lead to minimal progress in the service life of the batteries. (**AP A.1**)
- The most important recycling-relevant information is the cell chemistry used in battery systems and cells. Color-coded labels on battery systems, modules and cells are intended to provide information about the cell chemistry (e.g. “NCA”, “NMC”, “LFP”). In addition, the BattG registration number according to UBA or the manufacturer's name itself should be stated so that the manufacturer can be clearly identified in accordance with the BattG. (**AP A.2**)
- The instructions required for dismantling can be provided through an extension of the already established IDIS system. (**AP A.2**)
- As a **centralized single-stage collection** concept is to be aimed for initially, an initial dismantling plant with a processing capacity of up to 5,000 BEV equivalents/year should be set up in the immediate vicinity of a cell processing plant.
- In the long term (from around 2020), a transition to **decentralized two-stage collection and dismantling** is recommended.

A.1.2 Project area B

- Battery detection and visualization software for multi-brand workshop diagnostic device programmed and installed
- Mechanical disruption of complete cell clusters is possible -> inertization necessary, however
- Mechanical dismantling of various battery systems and creation of dismantling

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

sequences and times, including the necessary dismantling tools

- Methodical evaluation of dismantling with regard to ease of dismantling and automation
- Design of automation solutions based on the aforementioned evaluation methodology (handling of battery systems, modules and cells)
- Design of alternative layouts and linking of dismantling systems with purely manual dismantling stations, as well as mixed manual and automated dismantling stations
- Design of a gripper for the automated handling of battery cells with integrated voltage and internal resistance determination
- Testing by gripping and PLC-based measurement data acquisition of three different pouch battery cells
- Derivation of requirements for the design of battery systems in accordance with Design for Recycling and Design for Environment
- Digestion, sorting and classification on an industrial scale are possible
- Wet, solvent-based separation of current collector film and active material is possible, but time-consuming
- Dry, mechanical separation can be implemented on an industrial scale with high active material purity and high yields
- Process developed for unmixed separation of coating and current collector film with >99% purity
- Need for pilot-scale implementation to fully characterize the process

A.1.3 Project area C

- In principle, electrodes and cells (laboratory scale) with sufficiently good electrochemical performance can be produced from reconditioned active materials.
- Process developed for direct recoating of carrier films with material from production waste
- Directly recoated materials from rejects have the same electrochemical quality as new materials No resynthesis required
- Successful synthesis of active material from slightly impure transition metal salt solution with comparable electrochemical performance
- Active material synthesis from contaminated transition metal salt solution successful, but poorer electrochemical performance with greater contamination
- Need for subsequent purification - especially with regard to depletion of aluminum - or high-purity separation (developed in **PB B**)
- Need for further clarification of the influence of impurities on the quality of recycling electrodes

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- Need for pilot plant for the actual production of recycling materials (without simulation of impurities)

A.1.4 Project area D

- Investigation of the mechanical ageing mechanisms (adhesive force, elasticity of the electrode layer) on standard material
- Investigation of two differently contaminated NMC active materials.
- Slightly contaminated NMC material shows similarly good electrochemical performance as the original material
- Highly NMC-contaminated material shows significantly lower performance than standard
- Impurities in NMC active material cause increased particle breakage after cyclization

A.1.5 Project area E

- The ecological evaluation of the LithoRec process as part of the life cycle assessment performed by the ÖkoInstitut in accordance with ISO 14040/14044 results in some significant net credits in the ecological impact categories considered in all the process steps examined. Recycling batteries using the LithoRec process can therefore be regarded as ecologically sound.
- The economic evaluation shows that the LithoRec recycling process in combination with mechanical processing could be operated economically from an annual volume of approx. 4.500 tonnes of systems or 15,000 BEV systems. Such a volume would be achieved between 2018 and 2020 if the market penetration of electric vehicles is high and the targets of the National Electromobility Development Plan - a fleet of one million electric vehicles in 2020 - are achieved.
- The originally planned manual opening and separation of battery cells, which competes with mechanical processing, is considered uneconomical.
- In addition to the volume of used batteries, their composition is a key driver of a financially self-sustaining recycling process. If lithium iron phosphate batteries are predominantly used in electric vehicles in the future, the break-even point of the overall process will only be reached at around 6.800 tonnes of systems or 21,000 BEV systems.
- The economic efficiency of individual processes can be significantly impaired by certain factors. The biggest factor is falling prices for the recovered recyclable materials, but also the additional input materials required (e.g. nitrogen).

A.1.6 Project area F

- Development of a ProdTect product model for a lithium-ion battery system
- Identification of requirements for general battery design with subsequent development

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

of design rules for dismantling-friendly battery design

- Drawing up construction catalogs for joining techniques, joining of bodies and forms of heat transfer
- The dependencies between battery and vehicle cannot be precisely specified without standardization or are too dependent on the respective manufacturers.
- Predefined/standardized installation spaces make it easier for battery manufacturers to develop modular systems.
- It is possible to cover all electrification levels with just a few basic modules
- Definition of approaches that require complete implementation in CAD with prototypical CAD implementation.
- Development of a concept for the safe handling of high-voltage components of the battery system
- Identification of quickly realizable safety concepts for the aspects of transport and dismantling
- Compilation of the legal requirements for professional dismantling and recycling and derivation of proposals for documentation in IDIS and as a recycling passport

A.1.7 Project area G

- Conceptual design of a possible recycling pilot plant from the individual steps of the previous project areas
- Completely new plant on a greenfield site
- Consolidation of the results from the other project areas
- Layout concept of a system for processing 700 kg of cell material
- A process flow chart was created
- Individual system components, machines and devices were designed and possible suppliers identified

A.2 Publications

Publications

[Schmitt, 2011] Schmitt, J.; Haupt, H.; Kurrat, M.; Raatz, A.: Disassembly Automation for Lithium-Ion Battery Systems Using a Flexible Gripper. In: Proc. 15th IEEE International Conference on Advanced Robotics (ICAR), Tallinn, Estonia, 2011, ISBN 978-1-4577-1157-2

[Hanisch, 2011] Hanisch, C., Haselrieder, W., Kwade, A.. (2011). Recovery of active materials from spent lithium-ion electrodes and electrode production rejects in: Hesselbach, J.:, Herrmann, C.(Eds.): Globalized Solutions for Sustainability in Manufacturing, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Brunswick, Brunswick, Germany, May 2nd - 4th, 2011,

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Springer-Verlag, Berlin, Heidelberg, 85-89

[Hanisch, 2012] Hanisch, C., Haselrieder, W., Kwade, A.. (2012). “Recycling of lithium-ion batteries - the LithoRec project” in: Thome-Kozmienski, K.J.:, Goldmann, D.(ed.): Recycling und Rohstoffe, Volume 5, ISBN 978-3-935317-81-8, TK Verlag, Neuruppin, pp. 691-698

[Herrmann, 2012] Hermann, C.; Raatz, A.; Mennenga, M.; Schmitt, J.; Andrew, S.: Assessment of Automation Potentials for the Dismantling of Automotive Lithium Ion Battery Systems. In: Proc. 19th CIRP International Conference on Life Cycle Engineering, Berkeley, USA, 2012

[Hoyer, 2011a] Hoyer, C.; Kieckhäfer, K.; Spengler, T. (2011): Strategische Planung des Recyclings von Lithium-Ionen-Traktionsbatterien, in: Sucky, E.; Asdecker, B.; Dobhan, A.; Haas, S.; Wiese, J. (eds.): Logistikmanagement: Herausforderungen, Chancen and Lösungen, Band II, Tagungsband der Logistikmanagement 2011, University of Bamberg Press, Bamberg, pp. 399-419.

[Hoyer, 2011b] Hoyer, C.; Kieckhäfer, K.; Spengler, T. (2011): A Strategic Framework for the Design of Recycling Networks for Lithium-Ion Batteries from Electric Vehicles, in: Hesselbach, J.; Herrmann, C. (eds.): Globalized Solutions for Sustainability in Manufacturing, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Brunswick, Brunswick, Germany, May 2nd - 4th, 2011, Springer-Verlag, Berlin, Heidelberg, 79-84

Lectures and presentations

- 12th Doctoral Workshop Northeast (April 2010, Cottbus):
  “Network and process design for the recycling of lithium-ion traction batteries” (Claas Hoyer)
- 5th Conference of Car Recyclers (November 2010, Hohenroda):
  “LithoRec - Recycling of lithium-ion batteries” (Gunnar Bärwaldt)
- Battery Day in Aachen, (February 2011, Aachen):
  “Recycling of lithium-ion batteries using the example of LithoRec” (Arno Kwade)
- Kraftwerk Batterie, (March 2011, Aachen):
  “LithoRec - Processing of lithium-ion batteries for the hydro-metallurgical recovery of lithium and transition metals” (Arno Kwade)
- EUROFORUM conference “Raw materials for e-mobility” (May 2011, Stuttgart):
  “The LithoRec project: recycling EV batteries” (Arno Kwade)
- 6th Conference of Car Recyclers (November 2011, Hohenroda):
  “LithoRec - Recycling of lithium-ion batteries - The results” (Stefan Andrew)
- Materialica - Materials for Batteries - Congress (November 2011, Munich):

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

"Sustainability - Recycling of Lithium-Ion-Batteries" (Christian Hanisch)

- "From rechargeable batteries to zinc-carbon - developments in battery disposal", (November 2011, Potsdam): "Recycling lithium-ion batteries" (Christian Hanisch)
- Advanced Battery Power, (March 2012, Münster): "Recycling of Lithium Ion Batteries" (Christian Hanisch)

Poster

B. Hoffmann, S. Krüger, H. C. Wagner, F. Schappacher, S. Nowak, S. Passerini, M. Winter *'Recycling of Lithium Ion Batteries - Analysis and Methods'*, Kraftwerk Batterie - Lösungen für Automobil und Energieversorgung, Aachen, 01. - 02.03.2011.

S. Krüger, C. Hanisch, W. Haselrieder, S. Nowak, S. Passerini, A. Kwade, M. Winter *"Recycling of Lithium-Ion Batteries"*, 118th International Conference on Solid State Ionics, Warsaw, Poland, 03. - 08.07.2011.

H. Haupt, D. Wedler, "Ansätze zur demontagefreundlichen Batteriegestaltung", Kraftwerk Batterie - Lösungen für Automobil und Energieversorgung, Aachen, 01. - 02.03.2011.

Press article

- "Lithium - Ein Spannungsmacher auf Kreislaufkurs", article VDI nachrichten, 07.01.2011 based on interview with Professor Kwade.
- "Wiederverwertung Recycling im Elektro-Zeitalter", Süddeutsche Zeitung, April 27, 2011, based on interview with Christian Hanisch
- "Verifiably green", recycling magazine, issue 05/12 based on life cycle assessment and interview with Christian Hanisch

A.3 Definitions

Hybrid electric vehicles (HEVs) are passenger cars that can be powered by both a conventional combustion engine and an electric motor. Electrical energy is supplied from an accumulator, which is charged by recuperation (regenerative braking), for example. An all-electric drive mode is not a requirement.

Plug-in hybrid electric vehicles (PHEVs) are →*hybrid vehicles* whose batteries can be charged independently of the built-in combustion engine by connecting them to stationary charging devices. The possibility of purely electric operation for short to medium distances (~ 40 km) is a precondition.

Pure electric vehicles (Battery Electric Vehicles, BEV) are passenger cars that only have an electric drive. Electrical energy is supplied by an accumulator that can be charged by connecting it to stationary charging devices.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

PHEVs and BEVs are combined under the term **electric vehicle**.

Battery management systems (BMS) are electronic systems that ensure the functional safety of a battery system. Additional functions can include operating data acquisition and processing. The design depends on the manufacturer.

In vehicle technology, a **package** is the geometric arrangement of components of an overall system in relation to each other. The positions can be described by so-called package dimensions.

Modularization describes the possibility of building different overall systems from the variation of small basic bodies. The base bodies require defined interfaces for this

Templates are a template for a geometric body in the CAD system in which modeling steps can be stored. Using input parameters, a known geometry can be generated quickly in this way.

A Analysis and development of logistical collection and Feedback processes

A.1 Analysis of the volume of used batteries

The objective of **AP A.1** is to analyze and estimate the volume of used lithium-ion batteries from electric vehicles over time in order to create a planning basis for subsequent investigations in the individual project areas. Due to the high level of uncertainty, three scenarios are developed that reflect the expected spectrum of market and technology development in its entirety. These scenarios, which among other things specify the electric vehicle market stock for future points in time and the average service life of traction batteries, are then used to estimate the volume of used batteries over time with the help of a newly developed system-dynamic simulation model.

A.1.1 Identification and analysis of the influencing factors relevant to the reflux of used Li-ion batteries

The aim of this step is to identify and investigate the influencing factors that determine the volume of used batteries. This work was performed by AIP-TUBS in cooperation with AUDI. The identified factors can be divided into exogenous and endogenous factors. The main exogenous factors are (see Annex 1): The market development for motor vehicles that use a lithium-ion traction battery (A1 - A4), the service life of these vehicles (A5), the service life of batteries in mobile operation (C3) and the re-use of used batteries outside the system (D1, D2).

The influencing factors must be considered separately for the battery variants and drive concepts investigated in the project, as the volume of used batteries depends largely on them. Furthermore, in the area of market potential, it should be noted that the medium-term and long-term market potential of a drive concept can differ. The other factors B1 to B4 as well as C1 and C2 (hereinafter referred to as *auxiliary factors*) do not have a direct influence on the total battery volume, but take into account the fact that this cannot be processed as a homogeneous mass due to the different chemical compositions of the battery variants. Rather, the battery variants differ, for example, in terms of their energy and/or power density, their

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

cycle stability and calendar ageing and thus their service life, as well as the maturity of the technology.

Depending on the issue at hand, the volume of used batteries can be specified in different ways using the auxiliary factors. For example, the mass and volume in relation to the battery system are more relevant for transporting the batteries, while the mass in relation to the cells is more decisive for determining capacities in the recycling process. As part of the investigations in **AS A.1.4**, only the number of system units and the mass of used batteries were recorded.

A.1.2 Development of a simulation model for estimating the reflux of used Li-ion batteries

AIP-TUBS developed a scenario-based system dynamics model in the "VENSIM" development and simulation environment to simulate, describe and analyze the volume of used batteries.[1] The model is conceptually divided into four modules (see Figure A-1). The **vehicle sales module** simulates the sales of new vehicles with different drive concepts over time. The new vehicles sold are included in the **vehicle stock module**, in which the vehicle stock is modeled. The number of vehicles is the sum of cumulative new registrations less cumulative scrappings. The number of scrappings over time is determined in the module by simulating vehicle ageing. The batteries of different variants installed in the vehicles are recorded in the **battery inventory module**, in which the ageing and subsequent deinstallation and replacement of batteries of the vehicles in the vehicle inventory are simulated. The sum of vehicle scrappings and battery replacements is the volume of deinstalled batteries. The volume of used batteries available for recycling is shown in the used **battery volume module**, taking into account the delay caused by possible reuse. The model is parameterized using scenarios. Drive concept definitions, battery variant definitions and further use are specified exogenously.

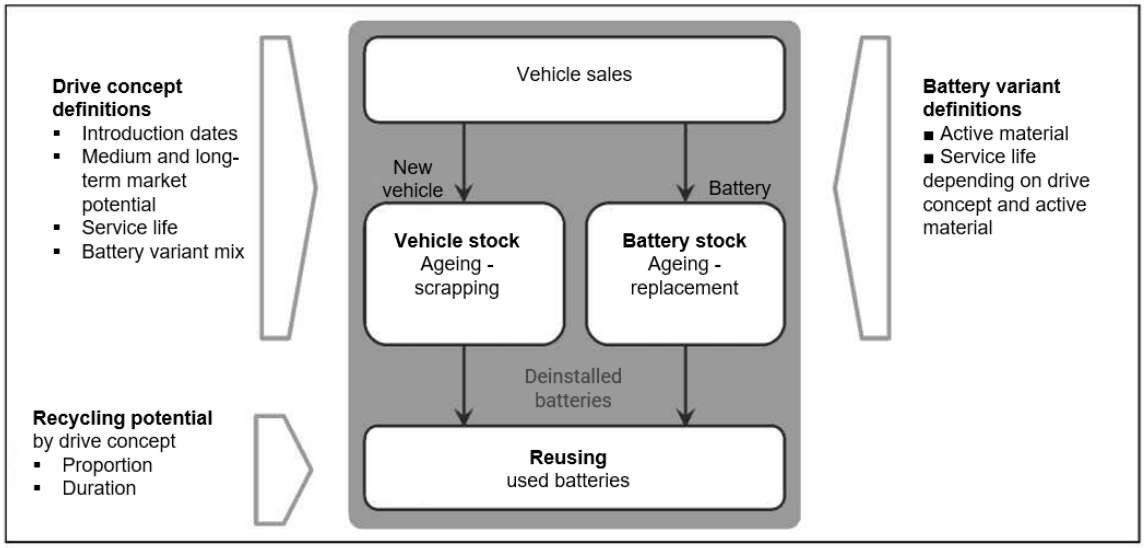


Figure A-1: Concept of the model for estimating the volume of used batteries

[1]For a scientific classification and presentation of an extension of this model, see Hoyer et al. (2011).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A.1.2.1 Description of the modules

The basic idea of the **vehicle sales module** is to calculate vehicle sales endogenously over time on the basis of exogenous scenario specifications. Total sales for the individual drive concepts are calculated on the basis of the sum of initial purchases and replacement purchases. While initial purchases are determined using a diffusion theory model based on Bass (1969), replacement purchases result from vehicle scrappage at the end of their useful life.

The basis for determining vehicle sales on the basis of initial purchases over time is a logistic growth function in the model. Vehicle sales correspond to inventory growth in the logistics function. In general, this growth depends on the current stock, an upper stock limit and a growth constant. In this case, the upper inventory limit is determined by the market potential. The growth constant is calculated in the model with the aid of exogenous scenario specifications. This includes the time of introduction of a drive concept and the expected vehicle stocks at two future points in time: the initial and the long-term market potential. The initial market potential allows the specification of a vehicle population expected in the near future (5 to 15 years). Expectations regarding the number of vehicles beyond this period in a saturated market can be taken into account with the long-term market potential. In addition, the model allows the mapping of transition technologies and thus the degeneration phase of a drive concept. If the long-term market potential is lower than the initial market potential, the number of replacements is limited until the stock of vehicles has also fallen to the long-term market potential.

The vehicles sold calculated in the vehicle sales module are included in the **vehicle stock module**, in which the ageing of the vehicles is simulated until they are scrapped. The ageing process of vehicles is modeled in so-called age cohorts.[2] This allows the total vehicle population to be classified into different age groups and vehicle scrappage can be determined on the basis of the expected average useful life and the failure rates differentiated by vehicle age. Vehicle scrapping leads to replacement purchases in the model, which are limited in the event of negative market growth.

The number of batteries removed from vehicles due to scrapping or ageing is calculated in the **battery inventory module**. The battery stock increases by the new vehicle battery requirement and the replacement battery requirement. The demand for new vehicle batteries is determined from the total sales of the respective drive concepts, taking into account the exogenous specification of drive concept-specific battery variant portions. Scrapping of vehicles reduces the stock. Aged batteries lead to a need for replacement batteries so that the stock of installed batteries remains constant. The ageing of the batteries is modeled in a simplified way; the batteries are deinstalled at the earliest when the vehicle is scrapped and at the latest when the battery service life is reached. The battery service life, differentiated according to drive concept and battery variant, is specified exogenously.

The used **battery volume module** is used to determine the used batteries available for recycling over time. The input variable is the number of uninstalled batteries from the battery stock module. The number of used batteries available for recycling is calculated from exogenous scenario specifications regarding the proportion of batteries in reuse and the duration of reuse. A distinction is made according to the drive concept in which the battery was

[2]Cf. Sterman (2000).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

originally installed. Using the specified drive concept and battery variant-specific masses, the total mass of the used batteries is determined over time.

A.1.3 Development of scenarios for the long-term development of sales and use of electric vehicles over time

Initially, there were no plans for AIP-TUBS to be involved in this step. In the course of the project, however, this appeared to be a valuable addition to the results of the project partners, so that the results of the AIP-TUBS on this work step are presented here. In collaboration with experts from AUDI, three scenarios were developed for the long-term development of sales and the use of electric vehicles over time. Following a list of the background assumptions, the assumptions of the individual scenarios are explained and the resulting parameterization is presented.

A.1.3.1 Background assumptions

The subject of the study is the expected volume of lithium-ion traction batteries in Germany that will have to be disposed of as waste after their use in hybrid, plug-in hybrid and electric vehicles due to vehicle scrapping, defects or reaching their maximum useful life. Due to the uncertain development of the market for vehicles and battery technology, the analysis is performed in a scenario-based simulation.

The **target value** of the simulation is the volume of used batteries. It is collected in the units quantity in units/a, mass in tonnes/a and nominal capacity in kWh/a, each broken down by drive concept. The calculation is based on the reference values in Annex 2.

The analysis covers a **long-term period** from 2010 to 2030. Longer time periods were also simulated to check system behavior in equilibrium, but these are not the subject of the evaluation in **AS A.1.4**. **Sales** of hybrid vehicles with a standard lithium-ion battery will start in 2010, while plug-in hybrid and all-electric vehicles will be available on the German market from 2012. The basis for calculating the market share of electromobility is **a long-term annual car sales volume** of 3.3 million vehicles on the German market.[3]

A.1.3.2 Scenario assumptions

Oil price, market and technology developments as well as the reuse and recycling potential of traction batteries were identified as drivers of the volume of used batteries. Table A-1 describes the assumptions of the market and technology development scenarios. Based on the scenario assumptions described above, a parameterization was performed in accordance with the influencing factors determined in **AS A.1.2**, which can be found in Table A-2 to Table A-5.

[3]Estimated on the basis of car registration figures, see Federal Statistical Office (2009).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Table A-1: Description of the assumptions of the market and technology development scenarios

Drivers	Pessimistic scenario	Political scenario	Realistic scenario
Oil price	Rising only slightly	Rising sharply	Rising extremely rapidly
Market	No or ineffective incentive programs High surcharges, no compensation through operating costs	Successful market activation, conveyors to manufacturers reduce their risk, surcharges are compensated by low operating costs and concessions	Targeted incentive programs Moderate surcharges are compensated by comparatively low operating costs
Technology	Many manufacturer-specific solutions, complicated international charging Hardly any progress in battery technology, low range and battery life	Late standardization in terms of batteries and their charging as well as electric drive; progress in terms of efficiency, range and reliability of batteries	Extensive standardization with regard to batteries, their charging and the electric drive Technological leaps lead to long range and long battery life
Reuse/recycling	Low suitability and hardly any demand for stationary use	High suitability, but little demand for stationary use	High suitability and demand for stationary use, high financial residual value
Consequences	**Alternative fuels and optimized conventional combustion engines prevail, hybrid and electric vehicles remain marginal phenomena**	**Accelerated market growth for PHEVs and BEVs, very high market shares in the long term (approx. 60 percent) Stock 2020: 1 million electric vehicles (PHEV + BEV)**	**Natural market growth for PHEVs and BEVs, comparatively high shares of BEVs are sold due to the long ranges**

Table A-2: Scenario parameterization, market development drive concept (A1 - A5)

Scenario	Pessimistic			Political			Realistic		
Parameters	Drive concept			Drive concept			Drive concept		
	HEV	PHEV	BEV	HEV	PHEV	BEV	HEV	PHEV	BEV
Initial market potential (A1) [1,000 vehicles]	100	200	50	200	800	200	50	200	50
Time of achievement (A2) [Date]	2020	2020	2025	2030	2020	2020	2020	2020	2020
Long-term market potential (A3) [1,000 vehicles]	250	300	250	150	15,000	5,000	150	12,000	8,000
Time of achievement (A4) [Date]	2030	2030	2035	2040	2050	2050	2040	2050	2050
Aver. service life of the vehicle (A5) [years]	11	9	9	12	10	10	14	12	12

Table A-3: Scenario parameterization, ratio of battery variants used (C1)

Scenario	Pessimistic	Political	Realistic
Ratio LFP [percent]	20	20	60
NMC ratio [%]	70	70	30
LCA ratio [%]	10	10	10

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Table A-4: Scenario parameterization, service life of the batteries by drive concept (C3)

Scenario	Pessimistic	Political	Realistic
HEV useful life [months]	50	72	180
PHEV service life [months]	42	60	96
Service life BEV [months]	36	48	60

Table A-5: Scenario parameterization, re-use/re-use outside the system (D1 and D2)

Scenario	Pessimistic			Political			Realistic		
	Drive concept			Drive concept			Drive concept		
Parameters	HEV	PHEV	BEV	HEV	PHEV	BEV	HEV	PHEV	BEV
Return delay (D1) [years]	—	—	2.0	—	1.0	2.0	—	2.0	4.0
Proportion of delayed returns (D2) [percent]	—	—	8	—	2	15	—	15	50

A.1.4 Performing a simulation study on waste battery returns with explicit consideration of uncertain influences

The simulation study was performed using the AIP-TUBS model developed in **AS A.1.2** in cooperation with AUDI. In the following, the results for the parameterization of the model with the three scenarios “Pessimistic”, “Political” and “Realistic” from **AS A.1.3** are presented and the scenarios are compared with each other. Due to the considerable uncertainties surrounding the volume of used batteries, the results of a sensitivity analysis are then evaluated.

A.1.4.1 “Pessimistic” scenario

The “Pessimistic” scenario can be regarded as the minimum scenario in terms of market development for electric vehicles. Based on these assumptions, the combined market share of electric vehicles (PHEV and BEV) will be less than 1 percent in 2020. It will rise only marginally to just under 2 percent by 2040. Pure electric vehicles in particular will not be sold in significant quantities until 2020.

In 2015, the volume of used batteries amounted to around 450 hybrid and 700 plug-in hybrid batteries (batteries from electric vehicles are negligible) with a total mass of around 120 tonnes. In addition to batteries from scrapped vehicles, this already includes the first replaced used batteries. In 2020, this will amount to just under 4.300 tonnes; in 2030, the volume will be around 22.500 tonnes. In the long term, a volume of around 30,000 t/a will be achieved from 2035.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

In addition to market growth at a low level, this result is also due to the very short service life of the vehicles (11 years for hybrid vehicles, 9 for plug-in hybrid and pure electric vehicles) and the batteries (approx. 4.2/3.5/3 years), which leads to a high frequency of vehicle scrapping and battery replacements. As only eight percent of batteries from all-electric vehicles are only reused or reused for an average of two years, most of them are available for recycling immediately after removal from the vehicles.

A.1.4.2 “Political” scenario

In the “Political” scenario, the target of one million electric vehicles on Germany's roads set out in the National Electromobility Development Plan is achieved in 2020. This figure is made up of 200,000 purely electric vehicles and 800,000 plug-in hybrids. The combined market share of electric vehicles is around 8 percent in 2020 and will grow to around 60 percent by 2040.[4]

Due to the early and rapid market growth of plug-in hybrid and electric vehicles in conjunction with the comparatively short service life of the vehicles and batteries and the only moderate importance of the reuse/recycling of batteries, the “Political” scenario leads to a very high volume of used batteries. In 2015, for example, scrapping will result in 26 hybrid batteries and a good 1.900 plug-in hybrid batteries as well as approx. 420 batteries from purely electric vehicles with a total mass of approx. 380 tonnes. In 2020, the figure is around 11.500 tonnes, which already includes the first old batteries to be replaced. For the year 2030, the volume will continue to grow strongly by approx. 150,000 tonnes.

A.1.4.3 “Realistic” scenario

In contrast to the “political scenario”, the “realistic” scenario assumes natural, i.e. not artificially accelerated, market growth. In the long term, electric mobility is expected to be similarly successful in this scenario. However, high market shares and stocks are reached much later. The combined market share of electric vehicles (PHEV and BEV) will be around 2.5 percent in 2020, but will rise to 32 percent in 2030 and reach around 60 percent by 2036.

In 2015, scrapping alone will result in a good 150 hybrid and 300 plug-in hybrid batteries as well as around 50 batteries from purely electric vehicles with a total mass of around 60 tonnes. In 2020, the figure will be just under 1,000 tonnes, and in 2030, the volume will grow rapidly to just under 29,000 tonnes. The initially very slow increase in the volume of used batteries is due to the long service life of both the batteries and the batteries and the high reuse rate.

A.1.4.4 Comparison of the scenarios

The annual waste volumes of spent batteries differ greatly between the scenarios and are growing at different rates. Figure A-2 shows a comparison of the waste battery volumes in the scenarios. With regard to the development of the composition **of used batteries over time**, there are major differences between the scenarios.

The total volume of used batteries in 2015 is between 70 and 400 tonnes. Most of these come from plug-in hybrid vehicles (50 to 270 tonnes). The mass of used batteries from hybrid vehicles is insignificantly low (less than 20 tonnes), batteries from purely electric vehicles are only expected in significant quantities in the political scenario (100 tonnes).

---

[4]Absolute market share as the ratio of the annual sales volume of one or more drive concepts to total passenger car sales.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

In 2020, the volume of used batteries is expected to range from 1,000 tonnes in the realistic scenario to 4,000 tonnes in the pessimistic scenario and 11.500 tonnes in the political scenario. The batteries continue to come primarily from plug-in hybrid vehicles. The proportion of hybrid vehicle batteries remains low. Batteries from purely electric vehicles continue to be insignificant in the pessimistic scenario, but in the other scenarios they account for a significant share of around one third in the political scenario (a good 4,000 tonnes) to half of the total volume of used batteries in the realistic scenario (just under 500 tonnes).

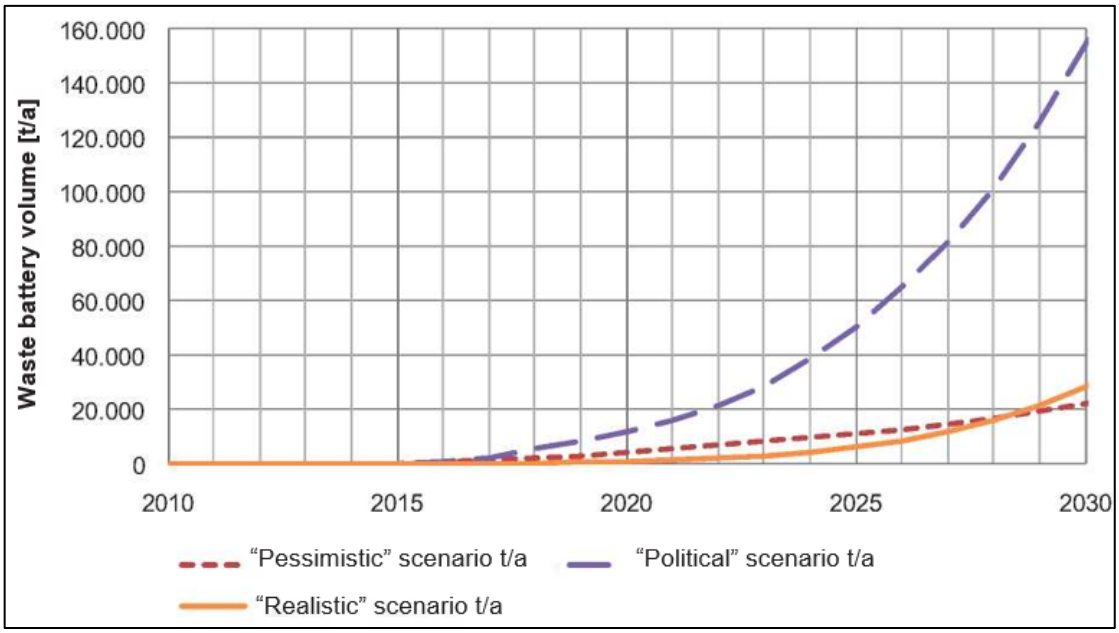
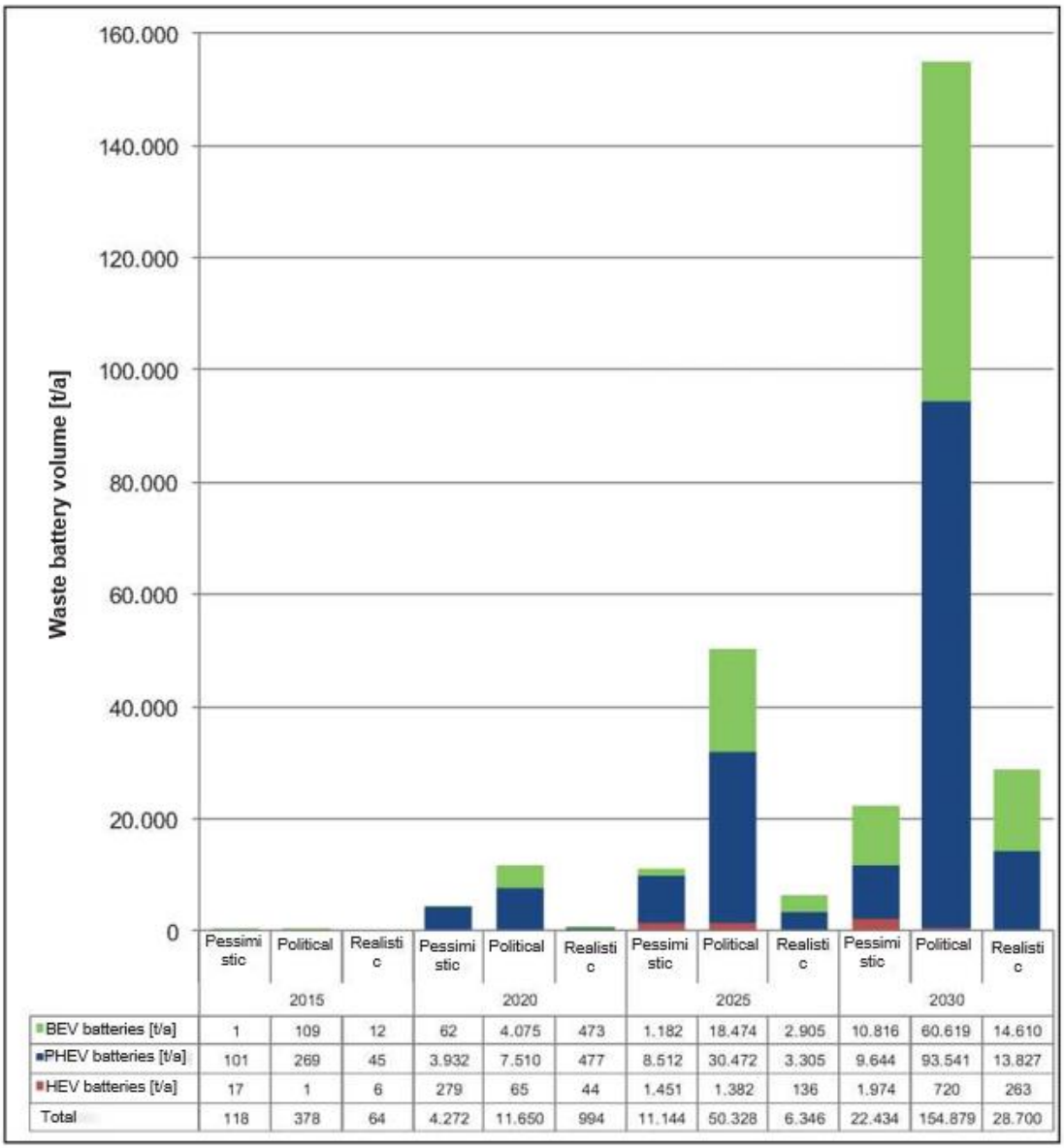


Figure A-2: Comparison of the used battery volume (mass) of the three scenarios

In the further course up to 2030, the annual volume of used batteries will grow on average between approx. 20% (pessimistic scenario) and 40% (realistic scenario) per year. The mass of waste batteries generated annually in the realistic scenario will only exceed that of the pessimistic scenario from around 2029. For the year 2030, the pessimistic and realistic scenarios result in used battery volumes of less than 22,000 and 29,000 tonnes respectively. The comparatively early and rapidly growing electric vehicle market in the political scenario leads to by far the highest volume of used batteries of around 150,000 tonnes. Hybrid vehicle batteries only achieve a significant share of 9 percent (approx. 2,000 tonnes) in the pessimistic scenario. Batteries from plug-in hybrid vehicles continue to contribute to a large proportion of the volume across all scenarios, but batteries from purely electric vehicles are becoming increasingly important and even exceed their share in the pessimistic and realistic scenarios.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.



	2015 Pessimistic	2015 Political	2015 Realistic	2020 Pessimistic	2020 Political	2020 Realistic	2025 Pessimistic	2025 Political	2025 Realistic	2030 Pessimistic	2030 Political	2030 Realistic
BEV batteries [t/a]	1	109	12	62	4.075	473	1.182	18.474	2.905	10.816	60.619	14.610
PHEV batteries [t/a]	101	269	45	3.932	7.510	477	8.512	30.472	3.305	9.644	93.541	13.827
HEV batteries [t/a]	17	1	6	279	65	44	1.451	1.382	136	1.974	720	263
Total	118	378	64	4.272	11.650	994	11.144	50.328	6.346	22.434	154.879	28.700

Figure A-3: Comparison of used battery volumes (mass) by battery variant in the three scenarios

Figure A-3 illustrates the development of the composition of used battery volumes in the three scenarios for selected points in time.

The differences between the scenarios become particularly clear when comparing the times at which the **threshold values for accumulated spent batteries** of 1,000, 10,000 and 100,000 tonnes are reached. They are reached first in the political scenario and last in the realistic scenario within the projection period.

The first 1,000 tonnes of used batteries are available for recycling in the political scenario in 2015, one year later in the pessimistic scenario and not until 2018 in the realistic scenario. The picture is similar for the first 10,000 tonnes; here too, the time gap between the political and pessimistic scenarios is only one year (2018 and 2019 respectively). In the realistic scenario, this threshold will not be reached until 2023. In the political scenario, the rapidly growing stocks of vehicles with lithium-ion batteries will lead to a cumulative volume of 100,000 tonnes of used batteries as early as 2023. This volume is only reached almost simultaneously five

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

years later in the pessimistic and realistic scenarios.

A.1.4.5 Sensitivity analysis

Due to the great uncertainty regarding the market and technological development of electric vehicles and traction batteries in particular, the impact of selected parameters on the volume of used batteries is being investigated.

A.1.4.5.1 Procedure

The endogenous variable to be investigated is the mass volume of used batteries by battery variant. The “Realistic” scenario serves as the basis for the analysis. Influencing factors that directly determine the volume of used batteries are the average **service life of the vehicles**, the **service life of the batteries** in mobile operation as well as the **return delay of the batteries** and the **proportion of delayed batteries.** The influence of the variation of these selected parameters on the volume of used batteries is investigated with the aid of a Monte Carlo simulation. This is multivariate, so that several parameters are varied simultaneously. The characteristics examined are shown in Table A-6.

Table A-6: Parameters examined in the sensitivity analysis and their possible characteristics

Parameters	Characteristics examined
Average vehicle service life	Simultaneous, independent modification of the lifetimes of all three drive concepts service life follows triangular distribution with the parameters minimum Value (a), maximum value (b), most probable value (c) HEV: $a = 10$; $b = 16$; $c = 14$ *years* PHEV und BEV: $a = 9$; b = 16; c = 12 *years*
Service life of the batteries	Simultaneous, independent modification; triangular distribution HEV: $a = 4$; $b = 15$; c = 14 *years* PHEV: $a = 3{,}5$; $b = 10$; $c = 8$ *years* BEV: $a = 3$; $b = 6$; $c = 5$ *years*
Delayed return of used batteries and proportion of delayed returns	Simultaneous, independent modification. Duration of delay: HEV: no delay (0), PHEV and BEV: triangular distribution PHEV: a — 0,1; b — 2; c = 1 *year* BEV: $a = 0{,}1$; b = 5; c = 2 *years* Proportion of delayed batteries: HEV: 0 PHEV: (0,0; 0,2; 0,4; 0,6) BEV: (0,0; 0,2; 0,4; 0,6; 0,8)

A.1.4.5.2 Summary of the results

The sensitivity analysis shows that - in addition to the market development for hybrid and electric vehicles - the **service life of the batteries** is the most significant factor influencing the amount of used batteries (see Figure A-4). A reduction in the parameter results in an increase in the volume of used batteries.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

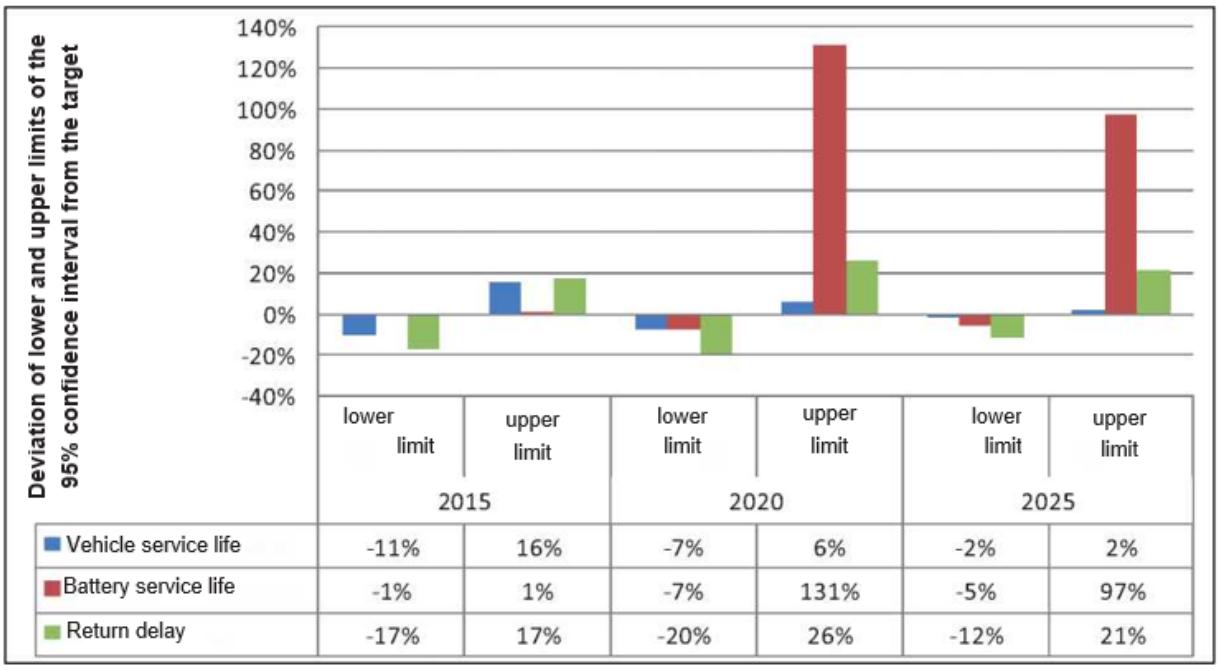


Figure A-4: Influence of selected parameters on the volume of used batteries

The comparison of the deviations of the lower and upper limits of the 95 percent confidence interval from the target value of the base scenario shows an up to 130 percent higher volume of used batteries in 2020 with the variation in battery usage duration. Figure A-5 shows the 50-percent, 75-percent and 95-percent confidence intervals (red, orange and green) of the expected used battery volume and the entire spectrum of all realizations (grey). The unit of measure on the ordinate is kilogram.

The variation of the **return delay results** in a maximum increase of +26 percent in the significant range in 2020. However, the S-shaped waste battery generation curve is merely shifted, i.e. the waste batteries arrive in the same quantity but with a time delay.

Extending or shortening the **vehicle's service life** still results in short-term deviations of up to 16 percent. Only in the case of hybrid vehicles, however, is there a clear impact on the volume of used batteries. Due to the minor importance of the hybrid vehicle market, its influence will decrease in the long term. In the case of plug-in hybrid and electric vehicles, it is reasonable to assume that a far more significant proportion of the used battery volume is caused by battery replacement due to the shorter battery service life, while the hybrid batteries in the baseline scenario reach at least the average vehicle service life and therefore only need to be replaced when the average vehicle service life increases significantly.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

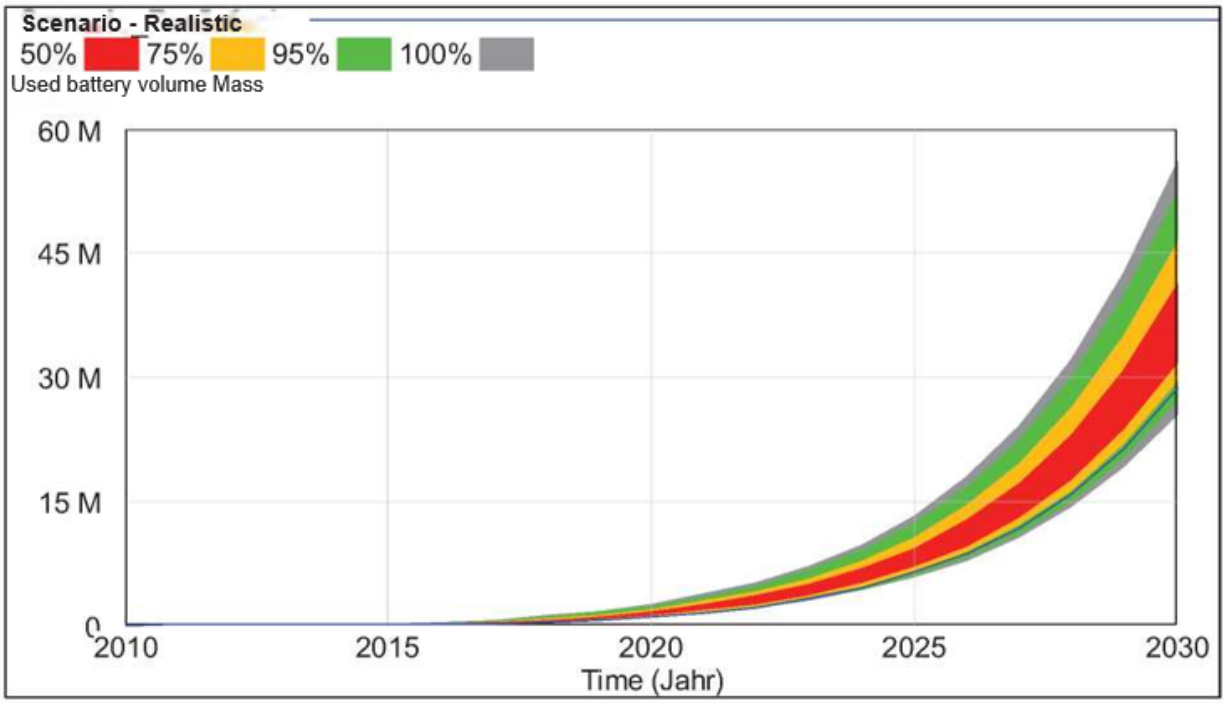


Figure A-5: Influence of battery service life on the volume of used batteries (kg/a)

A.2 Analysis and design of information flows

A.2.1 Analysis and adaptation of the information supply and requirements for the expansion and testing processes

As part of the project work, the common installation positions of the high-voltage battery in the vehicle were examined. Currently common installation locations for HV batteries are the spare wheel well in the trunk, behind the rear seat bench in the trunk, on the vehicle underbody in front of the rear axle, on the vehicle underbody in the tunnel and in the engine compartment.

In the case of full hybrids or electric vehicles, the battery block can be divided into several installation locations. Check whether there are other HV batteries in the vehicle. The installation locations vary for design, drive concept-specific and vehicle dynamics reasons.

In an ELV dismantling facility, the three qualification levels listed in Table A-7 are required depending on the specific activities:

Table A-7: Qualification levels for work on vehicles with high-voltage components

Qualification levels for work on vehicles with high-voltage technology	
Electrically trained person **(EuP)**	The EuP may: • perform general work and maintenance on the vehicle; • The SFAO-HV commissioned mechanical work on the de-energized high-voltage system.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Qualified electrician for specified tasks for work on the dismantling of HV systems of hybrid and electric road vehicles **(EFK-HV**)	Due to its qualifications, the SFAO-HV has the same powers as a EuP. In addition, the SFAO-HV: • perform the certified measurement of the absence of voltage in the high-voltage system, • perform the following work on the high-voltage system: ➢ ensure freedom from voltage ➢ secure against restarting ➢ determine and document the absence of voltage. ➢ commission EuP to work on the voltage-free high-voltage system.
Electrician (**EFK**) with additional qualification of an EFK-HV	The EFK may perform all the work of an EuP and an EFKHV and is authorized to perform all live work if a vehicle cannot be de-energized.

✓ **The current regulations are sufficient. However, a precisely defined description of the qualification as an electrician for specified activities for work on the dismantling of HV systems of hybrid and electric road vehicles (EFK-HV) would be recommended.**

The following Table A-8 describes the corresponding qualification levels depending on the individual hazard potentials of the activities performed in the ELV dismantling facility:

Table A-8: Qualifications required depending on activity and hazard potential

Vehicle condition	Activity	Qualification level	Comment
Standard vehicle	Non-electrical activities e.g. operating vehicles	None	Instruction on: no work on or in the vicinity of HV systems
Standard vehicle	Non-electrical activities in the vicinity of HV components e.g. mechanical activities (draining operating fluids, ...)	Electrically trained person	Instruction in writing about: - Do not work on or near HV systems, - Contact partner, - Additional safety measures
Standard vehicle	Electrical engineering activities, e.g. ensuring voltage-free operation	Qualified electrician for specified activities (HV systems on vehicles)	Successful training as a qualified electrician for specified activities (HV systems on vehicles) Written appointment as an EFK-HV (Electrical Safety Officer) Written instruction on: - no work on live HV systems
Prototypes and accident vehicles with damaged	All electrical and non-electrical work on the vehicle	Analogous to standard vehicle + additional	In addition to series vehicles, all activities require written

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

HV components		qualification for live working (electrician - EFK)	instruction Written appointment as EFK + EFK-HV

The following table summarizes some recommendations for necessary regulations.

Table A-9: Recommendations for regulations to be made

Work step	Qualification	Regulatory recommendation
Vehicle identification with HV systems	**EuP**	None
Read out battery parameters from the battery management system	**EFK-HV**	Regulations on data storage and evaluation required
Disconnect the 12V vehicle electrical system battery (optional)	**EFK-HV**	
Identify high-voltage battery type	**EuP**	
Visually check the high-voltage battery for damage	**EuP**	Regulations required for handling HV batteries damaged in accidents
Disconnect the high-voltage battery and secure against reconnection	**EFK-HV**	Sufficiently regulated in BGV A3 BGI 8686 DIN VDE 1000-10 DIN VDE 0105-100 BetrSichV TRBS 1203
Check that there is no voltage	**EFK-HV**	VDE 0413 Only use measuring devices that comply with VDE 0682-401 → No multiple measuring devices
Document absence of voltage		
Remove HV battery from vehicle	**EuP**	Manufacturer and vehicle-specific information for recyclers
Unlocking/securing the HV system on prototypes and damaged accident vehicles	**EFK + EFK-HV**	Inclusion in manufacturer and vehicle-specific information
Check HV battery for damage and suitability for transportation and storage	**EuP**	Regulations required for handling HV batteries damaged in accidents
Internal transportation and storage		Comply with storage and transportation regulations
Handover of the HV battery to the logistics company/battery recycler including the associated service plug	**Dangerous goods officer**	Simplification regulation recommended for recyclers

A.2.2 Analysis and adaptation of information supply and demand for the transportation process

Dangerous goods regulations for the transportation of lithium cells and lithium batteries

Lithium batteries are generally subject to the transportation regulations for dangerous goods. In principle, each cell and battery must correspond to a type for which it has been demonstrated that it meets the requirements of the tests in the Manual of Tests and Criteria, Part III, subsection 38.3. Otherwise, transportation can only be performed in accordance with

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

special regulations or by issuing official exemptions. The term “lithium batteries” covers the components “lithium cell”, “cell blocks, battery modules, battery packs and battery assembly units” consisting of several cells. The transportation requirements of the above dangerous goods classifications also apply without restriction to the transportation of used lithium batteries for the purpose of disposal or recycling.

Basic requirements (see special provision 230)

The cell or battery is equipped with a protective device against internal overpressure or is designed in such a way that a forced rupture under normal transportation conditions is prevented. The cells or batteries are equipped with an effective device to prevent short circuits. Batteries with several cells or with cells connected in parallel are equipped with an effective device to prevent dangerous reverse currents.

If the requirements are met, the cells/batteries must be packaged in accordance with the specifications of packaging instruction P903.

Used batteries

For the transportation of used cells and batteries by road/rail, the requirements of packaging instruction P903a and for collection P903 b apply. The packaging must comply with the test requirements of packaging group II. However, the packages must not exceed 30 kg gross weight.

These regulations do not apply to sea and air transport.

Transportation of “used” and/or “damaged” lithium batteries

Always check that the battery is in a safe condition for transportation. Neither the land transport (ADR/RID) nor the maritime transport (IMDG Code) dangerous goods transport regulations define the conditions under which a cell/battery is to be considered damaged. Only in air transport are criteria defined in special regulation A 154 that result in a transport ban (ICAO-TI/IATA-DGR). In compliance with § 4 GGVSEB, “Safety obligations” and § 3 GGVSEB, “Approval for transportation”, damaged batteries cannot be handed over for transportation without further ado.

As a result, an individual exemption is required for the legal transportation of damaged batteries in accordance with the provisions of Section 5 GGVSEB. The consequences are serious:

- Cross-border transportation and thus cross-border disposal of such cells and batteries is excluded.
- Considerable time, personnel and material expenditure in connection with the application for a permit.
- Effective and cost-effective disposal is made considerably more difficult or, if cross-border disposal is necessary, impossible.
- A particular obstacle is the fact that, under current law, an exemption may only be granted for individual cases, i.e. for one transport operation at a time.

Necessary measures

To ensure smooth and legally compliant transportation in logistics, including disposal logistics, the following measures are essential:

Amendment/legal update of the dangerous goods transport regulations

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

a) Amendment of the UN recommendations with the following objectives

- Introduction of regulations for the transportation of used lithium cells and batteries.
- Introduction of a label for cells/batteries that comply with SV 230.
- Description or definition of criteria for cells and batteries that are damaged or not safe for transportation.

b) Amendment of the ADR with the following focal points

- Modification of the packaging regulations for used, undamaged cells and batteries analogously for new, undamaged cells and batteries.
- Introduction of a packaging regulation for damaged cells and batteries that are not safe to transport.
- Clarification of the applicability of SV 310 for damaged pre-series and prototype cells/batteries that are not safe to transport.

c) Amendment of the IMDG Code with the following priorities

- Introduction of regulations on the transportation of used cells and batteries.
- Introduction of a packaging regulation for damaged cells and batteries that are not safe to transport.

The need for changes to dangerous goods legislation must be brought to the relevant bodies at international level. To this end, proposals are to be drawn up through the industry associations, which are then to be pushed through to the international meetings through the national authority representatives.

Environmentally sound disposal and transportation for disposal cannot be considered separately. A coordinated approach between the ministries BMU, BMVBS and BAM is required for the further development of the regulations.

A.2.3 Analysis and adaptation of information supply and demand for the storage/collection process

As part of the take-back process for used lithium-ion battery systems, storage locations are provided at various process participants. The process begins with the parties involved, who determine the technical condition of the battery system and decide whether it is a damaged system or an intact system.

The battery systems are removed by a workshop or an end-of-life vehicle recycling company. The battery systems are temporarily stored here until they are collected by the take-back logistics company. Depending on the logistics concept, the battery systems are consolidated in an interim waste storage facility (logistics hub) or taken directly to a recycling plant. At the recycler, the battery systems are taken to the incoming warehouse and then fed into the recycling process. When designing the storage area of the workshop, it should be noted that new battery systems, which serve as a replacement for the dismantled system, are also temporarily stored on site.

In work step **AS A.2.3**, AUDI should analyze the existing safety regulations for the storage of Li-ion batteries and the design of storage rooms for Li-ion batteries and identify or derive any need for optimization. Lithium-ion battery systems are classified as dangerous goods of hazard class 9 (various dangerous substances and articles) in accordance with the international regulations on the transportation of dangerous goods. Packaging group II indicates a dangerous good with **medium hazard**. However, dangerous goods legislation only considers

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

transportation; storage requirements are generally dealt with by hazardous substances legislation.

The term hazardous substances is defined as substances, preparations and products that have dangerous physical or chemical properties for employees. The regulations of the Hazardous Substances Ordinance aim to make the handling of hazardous substances as safe as possible. As the battery systems are not substances, preparations or articles within the meaning of the German Product Liability Act. Hazardous Substances Ordinance, the battery systems are **not** subject to the provisions of the Hazardous Substances Ordinance and the subordinate regulations.

As the battery systems contain a highly reactive battery electrolyte as the main chemical hazard carrier, the safety instructions determined by Merck for a battery electrolyte in accordance with hazardous substances legislation were used as an example. In the absence of existing safety regulations for Li-ion battery systems, these safety instructions could be used as a guide for handling the battery systems. It is particularly useful to observe these safety instructions for damaged battery systems. For the storage of used battery systems (non-defective or prototypes) in containers, **TRGS 510** *"Storage of hazardous substances in portable containers"* appears to be a good guide.

Employer's liability insurance association regulations/occupational health and safety regulations

The trade association regulations/occupational health and safety rules shown in Table A-10 were examined with regard to special regulations on the handling and storage of Li-ion battery systems:

Table A-10: List of trade association regulations/occupational health and safety regulations

Abbreviation	Title
BGV	Employer's liability insurance association regulations for safety and health at work
BGR	Employer's liability insurance association rules for safety and health at work
BGI	Employer's liability insurance association information for safety and health at work
BGG	Principles of the employers' liability insurance association
GUV	Safety and health regulations of the German Social Accident Insurance Institutions
TRBS	Technical rules for operational safety

As part of the research, no regulations specifically relating to the handling or storage of Li-ion battery systems were identified, meaning that the recognized occupational health and safety regulations are currently to be used accordingly for the handling and storage of battery systems.

The car manufacturers have already published a guide "Safe handling of electric hybrid components in end-of-life vehicles" in the International Dismantling Information System (IDIS) to assist dismantling facilities. This contains general information on precautionary measures as

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

well as general handling and dismantling instructions. However, these IDIS guidelines have no binding effect on companies and are therefore for guidance purposes only.

Recommendation:

- ✓ ***It is recommended that in future the companies involved be provided with specific instructions and guidelines in the form of an employer's liability insurance association regulation for the handling and storage of Li-ion battery systems with regard to the design of measures to protect employees. Such an industry agreement on the handling and storage of HV lithium-ion batteries in service and trading companies in the automotive industry, coordinated with the employers' liability insurance association, was initiated in the last reporting period by the Volkswagen Group in cooperation with TÜV Rheinland. Such an industry agreement can be adapted in a similar way by the Association of German End-of-Life Vehicle Recyclers and distributed to its members.***

A.2.4 Identification of information from upstream processes that is required during the recycling process

The information required for recycling is determined by the necessary dismantling and dismantling work. In this project, the information requirements on the part of the recycler are only considered for batteries that are to be recovered and whose contents are to be recycled. Testing the batteries in order to reuse or recycle them is not the basis of the investigation here.

The processing of the battery in the recycling plant is divided into two main processes:

1. Dismantling of the batteries and separation into housing, electronics, cables and cells
2. Recycling of the cells with separation of the active materials, anode, cathode and Separator material.

The main aim is to obtain the active materials for the recovery of lithium.

The following information is required for each battery for dismantling in the LithoRec process:

- Battery type
- Cell type and cell chemistry
- State of charge
- Damage, if applicable

With the help of this information, the dismantling company can perform the treatment and prepare the fractions for subsequent recycling. Information on battery type, cell type and cell chemistry can be provided by standardized markings on the battery. The state of charge and possible damage must be determined using suitable diagnostic equipment in the respective process step. Alternatively, accompanying documents can be created, which would have to be created for each battery and can be clearly assigned (e.g. through the battery serial number).

If no information about the battery is available, the necessary information about the battery can only be determined with the help of the battery manufacturer. Without this information, cell type and cell chemistry can only be determined by analyzing the individual cell.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A.2.5 Design of a tool for the needs-based collection and provision of information and a concept for implementing the tool in a software solution

In the following, the results of the information supply and demand analyses of **AS A.2.1** - **AS A.2.4** are first summarized and grouped on the basis of the LithoRec process chain. Possible options for an information system (information instrument) in which all data is recorded and made available are then presented, process-specific requirements for such an instrument are discussed and a suitable recycling information system is derived (**AS A.2.5**).

A.2.5.1 Information flow along the process chain

First, the flow of information along the process chain was analyzed and determined. In order to be able to map this information flow as required, the process chain was extended to include the dismantling step. The grouping of information flows is therefore based on a process chain with five stages. This begins with the step of removing the battery from the vehicle and a subsequent test. The second step involves transporting the batteries from the removal site to suitable storage facilities. The third step involves storage and collection, step 4 the dismantling process and step 5 recycling.

Based on this grouping, the information relevant to the recycling process was identified in cooperation with the participating project partners AUDI, VW, EC and FRZ. The information flows in each process step were divided into product-related and object-related information. Product-related information includes static data of a battery or battery type, such as the battery identification number, the name of the battery manufacturer or the dimensions. Object-related information, on the other hand, contains battery-specific or dynamic data, such as the date the battery was removed from the vehicle or damage. Such separation is recommended, as the product-related data is not subject to confidentiality and can therefore be compiled by the battery manufacturers in a freely accessible database. The object-related data can be collected in the individual steps of the process chain, but due to its sensitivity it may only be viewed by a small number of authorized users.

After recording the times at which the relevant information was required (Annex 3), the range of information and suitable survey times were determined according to the criteria of “time” and “efficiency”. The “time” criterion is intended to ensure that all data was collected before the initial time of need. The “efficiency” criterion ensures that the data is collected at a point in time within the permitted time period when the effort involved is minimal. It can be seen, for example, that the battery manufacturer's details are required for the first time during removal and testing and must already be determined at this point. This information is also required in the subsequent storage and collection process. If the information is communicated between the processes, there would be no need to collect it again.

A.2.5.2 Options for collecting and providing information in line with requirements

Once the information flow along the process chain has been analyzed and determined, a suitable recycling information system has been developed for the collection and provision of information within the recycling network. Four data storage options were identified for this purpose: data storage of product and object-related data on the object/battery and central electronic storage of both data types.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Storage of product-related data on the object

Product-related information can be affixed to the object with the aid of stickers, labels or routing slips. This form of storage is associated with low initial investment, as these data carriers have a low material value and can be attached during the battery manufacturing process. In addition, no electronic devices are required to read the data during the recycling process. On the other hand, there is an increased risk of data loss due to damage or loss of the data carrier.

To reduce this risk, the alternative of electronic data storage at the property is being considered. RFID chips, for example, can be used for such storage. However, this requires a higher initial investment, as these chips can only be read with appropriate readers. These devices would have to be available for every player in the process chain and in some cases at every workstation. In addition, reading with these devices is more time-consuming than direct reading.

Central storage of product-related data

An alternative to data storage on the property is centralized electronic storage. With this option, the technical data for each battery type is stored in a database and can be accessed through a web browser. This type of information provision of product-related data is already guaranteed by the automotive industry through the “International Dismantling Information System” (IDIS) platform. However, Internet access is required at every workstation where information is needed. In addition, data collection is also more time-consuming and may be made more difficult by health and safety regulations (wearing gloves).

Storage of object-related data on the object

Object-related data can be retrieved as required within the respective process steps using suitable measuring and diagnostic devices and passed on along the process chain using suitable accompanying documents. The demand-dependent direct determination of property-related data on site offers high flexibility with regard to data characteristics and comparatively high integrity.

The option of an RFID chip can also be considered for the storage of object-related data. However, this form has corresponding disadvantages (see above). In addition, data transfer between players is difficult or impossible. For example, it is not possible to transmit information about the pick-up location and time directly to a freight forwarder.

In both options of decentralized data storage at the object, confidentiality of the object-related data is not guaranteed.

Central storage of object-related data

Centralized electronic data storage is also possible for the storage of object-related data. Here, the information for each battery can be stored in a database and can be viewed immediately by all players with the appropriate authorization. Such a system is capable of mapping large volumes of data and the data can be modified quickly and cost-effectively. However, Internet access is also required at every workstation and data maintenance is more time-consuming. There is also a great need for coordination regarding the data characteristics, which can mean different requirements due to the different concepts of battery systems, particularly in terms of functionality, but also along the process chain. Furthermore, the costs of such a database (e.g.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

due to the necessary data maintenance) could have a negative impact on the competitiveness of the recycling process investigated in LithoRec if databases are not required for other recycling processes.

Evaluation of the storage of data

None of the options presented for storing product or object-related data appears to be superior in all respects. Following a list of specific requirements for an information tool, two alternative concepts for storing and providing data are therefore presented below.

A.2.5.3 Requirements for an information tool

In order to select or develop a suitable instrument, requirements for an information instrument specifically for the LithoRec recycling process were identified and their relevance discussed in cooperation with the partners of **AP A.2**, i.e. potential actors in the process chain. Fast information provision and fast information retrieval (1) without the use of readout devices specific to a recycling process (2) were defined as fundamental requirements. Another requirement is the use of a standardized data structure (3) in order to be able to transmit information in a targeted and error-free manner. In addition, the information must be permanently accessible (4), i.e. every stakeholder must also be able to access information if the battery or

components are not actually present. This requirement is particularly helpful for transportation planning, as it must be possible to update transportation plans at any time. The platform independence of the instrument (5) was identified as a further requirement in order to avoid possible compatibility problems. In addition, object-related information should not be freely accessible, but should be made available in a targeted manner (6). Ultimately, the implementation of the instrument should have a good cost-benefit ratio (7).

A.2.5.4 Selection and structure of a suitable information tool

Due to the requirement for permanent access to the information and selective data access authorization, the options for electronic storage of property-related data at the property are no longer available. On the other hand, both a central electronic recycling information system in line with the requirements and on-site retrieval and individual forwarding along the process chain are practicable solutions. Product-related data could also be integrated into the central electronic system. This means that all information can be viewed “at a glance”. With regard to product-related information, however, storage on the object (e.g. identification number, active material type) by means of suitable labeling, as this data is not modified, is quickly accessible in this form and is not subject to any confidentiality interests. This allows the batteries to be identified quickly and reliably.

A.2.5.4.1 Process-oriented central database solution

On the basis of these findings, a recycling information system was schematically designed that connects the actors involved in the process chain and through which product-related information can be accessed and relevant object-related information can be exchanged.

The central point in this system is a database in which initial object-related data can be stored with the help of a battery data sheet in addition to the product-related data during the **manufacture of a battery**. This data sheet is called up and supplemented through a **battery identification number** when the battery is installed in the vehicle and when the battery is

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

modified (e.g. replacement of a module or a cell). The data sheet should be called up quickly and with little manual effort. This could be done through the battery management system, if still active, or through barcode/RFID chips on the system or module. In the following, the data sheet can be expanded with the relevant information for the actors involved in the recycling processes (Figure A-6).

Through the Internet, the players are enabled to access relevant information by using defined query functions and to retrieve or update this information in a targeted manner. To do this, an actor's browser establishes a connection to a web server. This web server accesses the central database through a defined logic, extracts the requested information and makes it available through the Internet. The security of the data against unauthorized access is regulated by setting up access rights for the users of the communication platform. Depending on the specific task and contract with the battery manufacturer/automobile manufacturer, each actor must be given read and write access rights. This agreement specifies which data an actor must provide and which information it can retrieve. A company is assigned to each user. The company affiliation directly influences the accessibility of the property-related information, so that this can only be exchanged between the companies between which corresponding contractual agreements have been made.

In addition to the advantages of centralized storage, the concept presented offers further benefits. On the one hand, the solution developed enables broad use by companies with different structures, from small and medium-sized enterprises to large companies. On the other hand, the data provided in the recycling information system can be used directly by every stakeholder. This direct transfer of data into the planning tools of the individual players allows the application of solutions for further operational planning. The creation and maintenance of the databases can be handled by an external service provider.

There are basically two options for implementing such a recycling information system. On the one hand, this can be implemented on a manufacturer-specific basis, and on the other hand on a cross-manufacturer basis. For example, each car manufacturer can create and operate such an information system or different manufacturers can implement a joint system. One advantage of a **manufacturer-specific system** is the ability to customize the information system. This ranges from the amount of data to the user interface. However, this form involves a high level of coordination effort for the players involved, as several systems have to be used and coordinated in parallel. With a **manufacturer-independent system**, on the other hand, there is a great need for coordination between the companies with regard to the development and design of the system. The subsequent implementation and application requires little effort. In addition, data access can be regulated to prevent data misuse. Another advantage of a comprehensive system is the possibility of having the system maintained and serviced by a service provider.

A.2.5.4.2 Product-oriented, needs-based individual solution

The comprehensive web-based database solution requires extensive coordination of all cell, battery and electric vehicle manufacturers for a holistic solution. In addition, costs are incurred for the technical implementation by the parties involved as well as costs for equipping the workshops, transporters, dismantling and recycling companies with appropriate reading/issuing and transmission devices. It should also be checked whether the data identified as necessary in the LithoRec process is required to the same extent in other possible recycling processes (e.g. pyrometallurgical processes).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

As these reasons make the use of the database solution appear difficult to implement, it is suggested that suitable labels be applied to battery systems, modules and cells to provide information about the cell chemistry (e.g. color-coded symbols “LFP”, “NMC”, “NCA”)

This means that product-related information can be made available to the entire process chain easily and cost-effectively without a great deal of coordination effort. Object-related information could also be obtained from those involved in the process using appropriate testing equipment if required.

The instructions required for dismantling, such as the installation location of the battery in the vehicle and the tools required, have already been provided through an extension to the IDIS database system. This contains a perspective view of the object, a tabular list of all technical data and specific dismantling instructions.

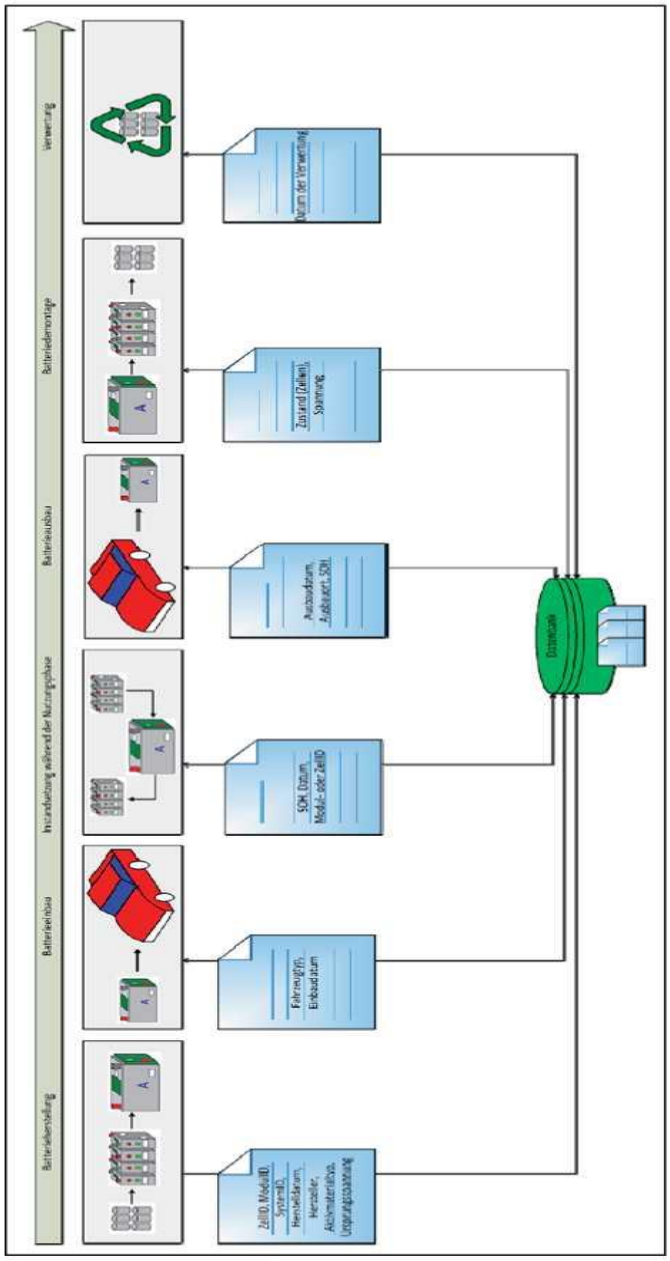


Figure A-6: Schematic representation of the recycling information system

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A.3 Development of collection concepts

A.3.1 Requirements analysis for potential networks for recycling Li-ion batteries

The result of the work step performed by AIP-TUBS and VW is the analysis of potential network constellations in the context of recycling lithium-ion batteries. In the following sections, the system boundaries are first defined, areas of activity in the system are defined and described and possible network players are identified. Three possible network constellations are derived from the findings. Finally, a catalog of requirements describes which requirements must be observed at network and process level.

The steps described below, from removal to material processing of the batteries and the associated players, are considered. Companies that use or recycle components and materials that can be reused or recycled are not included in the determination of network constellations. The production of new cells or batteries is therefore not considered.

A.3.1.1 Definition of system boundaries

Removing the used battery from the vehicle

The ageing of the lithium-ion traction battery of a hybrid/electric vehicle and the associated loss of capacity as well as irreparable defects in the battery lead to the need to replace the battery, whose service life may be significantly shorter than that of the rest of the vehicle.[5] The task of removal and installation can only be performed by specialists and special tools due to the electrical hazards involved and the mass of the batteries. Expansion by non-professionals is rather unlikely and is not taken into account in the analysis.

In the next few years, when comparatively few hybrid/electric vehicles are expected to be sold, only a few workshops will have the **necessary** expertise for the expansion and will have the appropriate specialists and tools available. For warranty, guarantee and customer loyalty reasons in particular, these will mostly be manufacturer-affiliated workshops (hereinafter referred to as authorized workshops). Due to the additional financial burden, manufacturer-independent workshops (hereinafter referred to as independent workshops) will initially only offer such services in exceptional cases. However, with the increasing population of hybrid/electric vehicles, a growing number of (independent) workshops are expected to discover the replacement of old batteries as a business segment.

End-of-life vehicle dismantling companies (hereinafter referred to as ELV dismantlers) will also be confronted with the removal of the end-of-life battery as part of the disposal of end-of-life vehicles. In principle, authorized workshops, independent workshops and end-of-life vehicle **dismantlers** should therefore be **considered** as potential **collection points** for traction batteries.

Examination

In order to be able to treat the used battery safely and efficiently, an **inspection** is necessary. The test provides information on the condition of the old battery and is the basis for a decision on the battery's usage path. It is the basis for estimating the monetary value of the used

[5] Sarre et al. (2004), for example, expect a service life of 5 years in electric vehicles and 15 years in hybrid vehicles for lithium-nickel-cobalt-aluminum oxide (NCA)-based batteries.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

battery and the costs associated with its treatment.

The degree of accuracy required for the test and the tools and devices that can be used to carry it out is not certain at present and depends in particular on the technical development of electric vehicles and batteries and on standards that have yet to be defined. In principle, the test can be performed at different intensities at several points in the recycling system:

- Sight and smell test. The battery is checked for obvious external damage. This inspection is necessary both before and after removal from the vehicle, before and after transportation and before dismantling.
- Readout of operating data (e.g. driving distance, maximum temperatures, faults that have occurred, voltage, SOH (State of Health) from the vehicle system, unless this data was only stored in the battery's own memory (BMS) (test A). Appropriately equipped authorized workshops (independent workshops and end-of-life vehicle dismantlers only if they have the appropriate diagnostic equipment) are eligible for this, as only they have access to the vehicle. Simple reading can be achieved with standardized readers developed for this purpose and network-wide information systems. Vehicle manufacturers in particular could be increasingly interested in evaluating long-term battery performance data and equipping selected authorized workshops with the appropriate equipment.
- Readout of operating data from the battery management system (test B). This inspection can be performed either directly after or decoupled from removal from the vehicle before sorting and storage. Accordingly, the above players and specialist disposal service providers are deployed.
- Test and measurement of the condition of individual components (test C). This test is necessary if the battery management system cannot provide sufficient information about the condition of individual modules or cells. Testing individual components requires a dismantled battery or a battery equipped with appropriate test leads. This task can only be performed by specialist waste disposal service providers.

Independent and authorized workshops as well as end-of-life vehicle **dismantlers** are eligible for test A and test B. Test C must be performed by **specialist waste disposal service providers** who can also perform test B.

Storage

Used batteries must be stored to bridge the gap, for transportation bundling and to form recycling lots until they are sold, reprocessed, disposed of (for material recycling) or disposed of. Sorting is necessary in order to be able to classify them according to their intended use and type.

Basically, a distinction must be made between a centralized and a decentralized collection concept with regard to storage. There is exactly one central warehouse in the **central collection concept.** It appears particularly attractive in the case of high capital intensity, economies of scale and relatively low transportation costs. A reversed initial situation speaks for the economic advantage of a **decentralized collection concept** in which at least two warehouses exist, each responsible for the collection of spent batteries from a defined region. Due to smaller catchment areas and thus shorter average distances, this concept is

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

particularly advantageous if workshops or end-of-life vehicle dismantlers do not have suitable short-term storage facilities. In addition, the possibility of pre-sorting and transport bundling speaks for a decentralized collection concept.

The establishment of upstream test stations (*test B*) should be investigated in view of the possibility of untested or incorrectly tested spent battery returns and in order to exploit learning effects. Before storing the old batteries for a longer period of time, a charge level adjustment should be performed. During storage, it may be necessary to (continuously) check the charge status. In this case, the warehouse would have to be equipped with appropriate devices. Both the storage of damaged used batteries and the prolonged storage of undamaged used batteries are potentially associated with fire and explosion hazards. The warehouses must be designed specifically for the storage of used batteries in vehicles, taking into account (yet to be created) legal regulations. Separate storage must also be provided for damaged batteries, e.g. in fireproof safety containers (F90).

Storage in connection with testing, sorting and separation of used batteries can only be performed by the battery manufacturer itself or by specialist companies (hereinafter referred to as **specialist disposal service providers**). If these steps were omitted, the used batteries would be transported to the dismantler unsorted in mixed fractions.

Transportation

Used batteries must be transported between collection points, any interim storage facilities and the dismantling and processing plant(s). Lithium-ion batteries are internationally classified as dangerous goods (UN numbers 3480 and 3481)[6]. Transport regulations such as the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) or the Agreement concerning International Carriage by Rail (RID) must be observed. The danger posed by defective batteries must be eliminated by suitable measures before transportation (deactivation). In the following consideration, batteries recognized as damaged are excluded from the above concepts.

In the case of a **bring concept**, the responsibility for transporting the used battery to the nearest collection point (warehouse or dismantling plant) lies with the party who removes the battery from the vehicle. This would require each of these actors to provide a suitable transport vehicle and/or approved transport containers for the used batteries. The joint use of a transport vehicle by several players in close proximity is possible. If the **collection concept** is used, the used battery transport is organized centrally by the warehouses or the dismantling plant. This can be performed by the warehouse or dismantling plant operator or an external logistics service provider. This concept also requires suitable transport vehicles and containers. In the **forwarding concept,** the transport tasks between the removal points and the warehouses or between the removal points and the dismantling plant are organized by a **logistics service provider** (LSP). Due to the storage requirements, the forwarding concept is only applicable in the central collection concept. The statutory regulations apply to vehicles and containers.

Dismantling

During dismantling, the old batteries are removed down to cell level. It can, but does not have to, lead exclusively to the recycling of used batteries. Rather, it seems sensible to replace individual defective components with functional ones in the sense of remanufacturing if the old

[6]Cf. UN (2008), p. 242 - 255, as well as Chapter 3.3, Special Provisions 188, 230 and 636 (p. 7, p. 11, p. 636).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

battery can be reused or reused as a result. To assess the use and recycling possibilities of the used batteries or their components, a detailed test must be performed using special measuring equipment before and during the dismantling of the batteries (test C). It may also be advantageous to set the old batteries to the lowest possible electrical charge before dismantling them, provided the battery management system allows this.

When dismantling, used batteries that are as similar in construction and/or condition as possible should be grouped together in batches. The batch formation, which requires prior sorting, eliminates the need for frequent tool changes and enables learning effects to be utilized. In this way, costs can be significantly reduced.

Due to the complexity and diversity of the products, the risks associated with handling used batteries (electrical voltage, fire and explosion hazards) and the capital intensity associated with partial automation, only specialist companies can be considered for this task. These can be **specialist disposal service providers** in particular, but also **active material manufacturer**.

Preparation

The aim of processing is to recover as much of the cell components as possible, in particular the active material containing valuable substances. For this purpose, the cells are processed using mechanical, hydrometallurgical and/or pyrometallurgical processing methods. This requires process engineering systems that are associated with high investments. Before treating the cells, it may be necessary to set the state of charge of the cells to “0 volts”.

The mechanical processing of the cells must be adapted to the hydrometallurgical processes in order to achieve a high recycling efficiency. **Specialist disposal service providers** and **active material manufacturers** can be considered for mechanical processing. Hydrometallurgical processes, on the other hand, require the expertise of chemical companies, e.g. **active material manufacturers**.

A.3.1.2 Determining network constellations

Various network constellations were identified on the basis of the characteristics highlighted in the activities mentioned.

A.3.1.2.1 Network constellation A - single-level collection concept

In **network constellation** A (see *Figure A-7*), test A and battery removal as well as optional **test B** are performed by independent and authorized workshops as well as by ELV dismantling companies. The used batteries are temporarily stored on site or, if there is no storage capacity, at a nearby authorized workshop. Used batteries are collected from one or more recycling plants according to the pick-up principle; tours can be formed to increase the capacity utilization of the transport vehicles. Transport can also be organized by a **freight forwarder** or **logistics service provider** (LDL).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

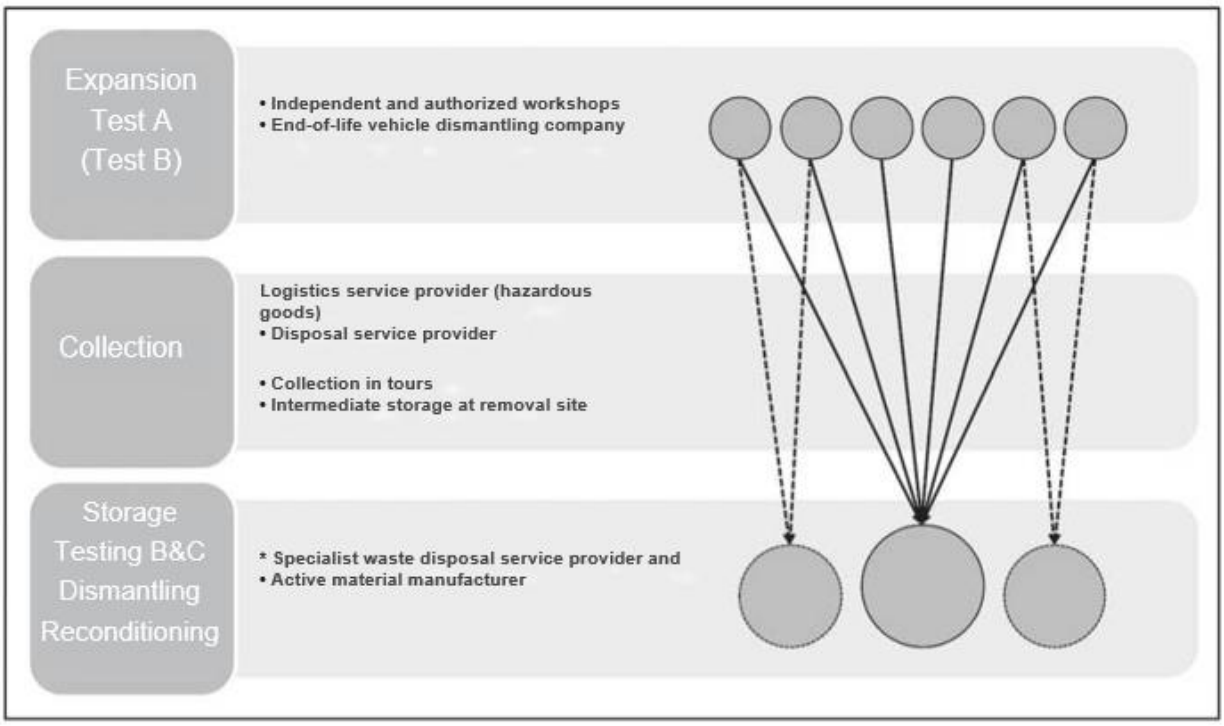


Figure A-7: Network constellation A - single-level collection concept

The recycling plants first perform a **B test** and sorting. The used batteries are stored there until further **treatment**. The batteries are grouped together in single-variant batches and then **dismantled** on site down to cell level. **Test C** is performed before each of the individual dismantling steps. Used batteries and components that can be reused or recycled are reconditioned as required. Cells that are no longer usable are sent for **reprocessing**. Residual material such as housings and cables are either processed on site or sent for external treatment or disposal. The recycling plants are operated by **specialist disposal service providers** and/or **active material manufacturer**s. These can, but do not have to, be legally independent of each other. Coordination of the network is either decentralized by each recycling plant for a predefined region or centrally by a focal company (e.g. a disposal service provider).

A.3.1.2.2 Network constellation B - two-stage collection concept with integrated dismantling and processing

In contrast to constellation A, in network constellation B (see *Figure A-8*) the spent batteries are collected from decentralized storage facilities immediately after removal, where they are tested (test B), sorted and stored. Directly recyclable/reusable used batteries are sold from here, and repair is also possible.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

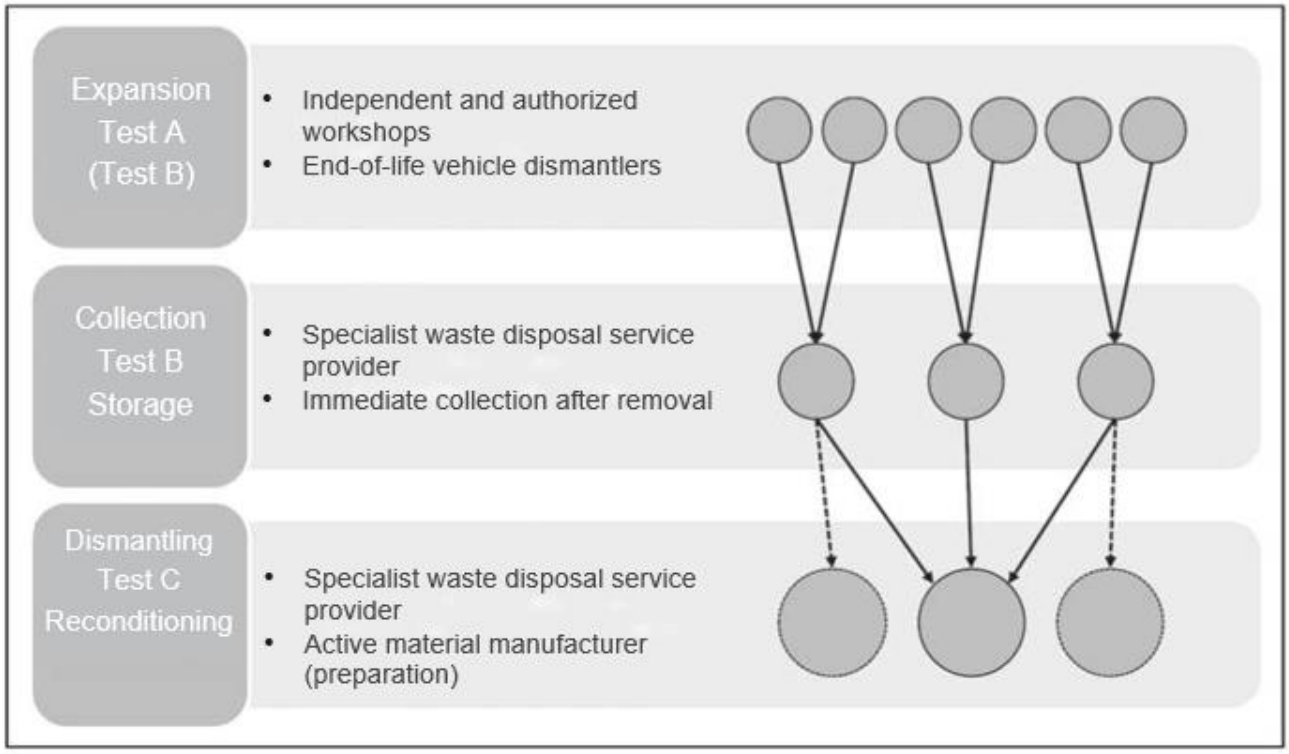


Figure A-8: Network constellation B - two-stage collection concept with integrated dismantling and processing

The warehouses and recycling plants are operated by **specialist waste disposal service providers**. The used batteries are only transported in batches to the recycling plant(s) if they are to be processed there. The coordination of the network is either performed decentrally by each recycling plant for a predefined quantity of warehouses in a specific region or centrally by a focal company (e.g. specialist disposal service provider). Network constellation A and network constellation B are not contradictory; rather, it is possible that a transition from constellation A to B will take place as the volume of used batteries increases, as transportation costs can be saved by setting up additional collection locations and then bundling transportation.

A.3.1.2.3 Network constellation C - two-stage collection concept with decoupled dismantling and reprocessing

Network constellation C (see *Figure A-9*) assumes the possibility of spatially decoupling the dismantling of used batteries and the processing of cells. In contrast to network constellation B, the used batteries are dismantled at the same location as they are stored. This means that used batteries can also be reconditioned there. One advantage of this alternative is that the usage path of the used batteries can be determined at an early stage and unnecessary transportation can be avoided. Only the cells are sorted and transported to one or more recycling plants. Storage and dismantling are performed by specialist waste disposal service providers and the processing plants are operated by active material manufacturers. The network is coordinated either decentrally by each dismantling plant for a predefined region or centrally/decentrally by one or more processing plant(s).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

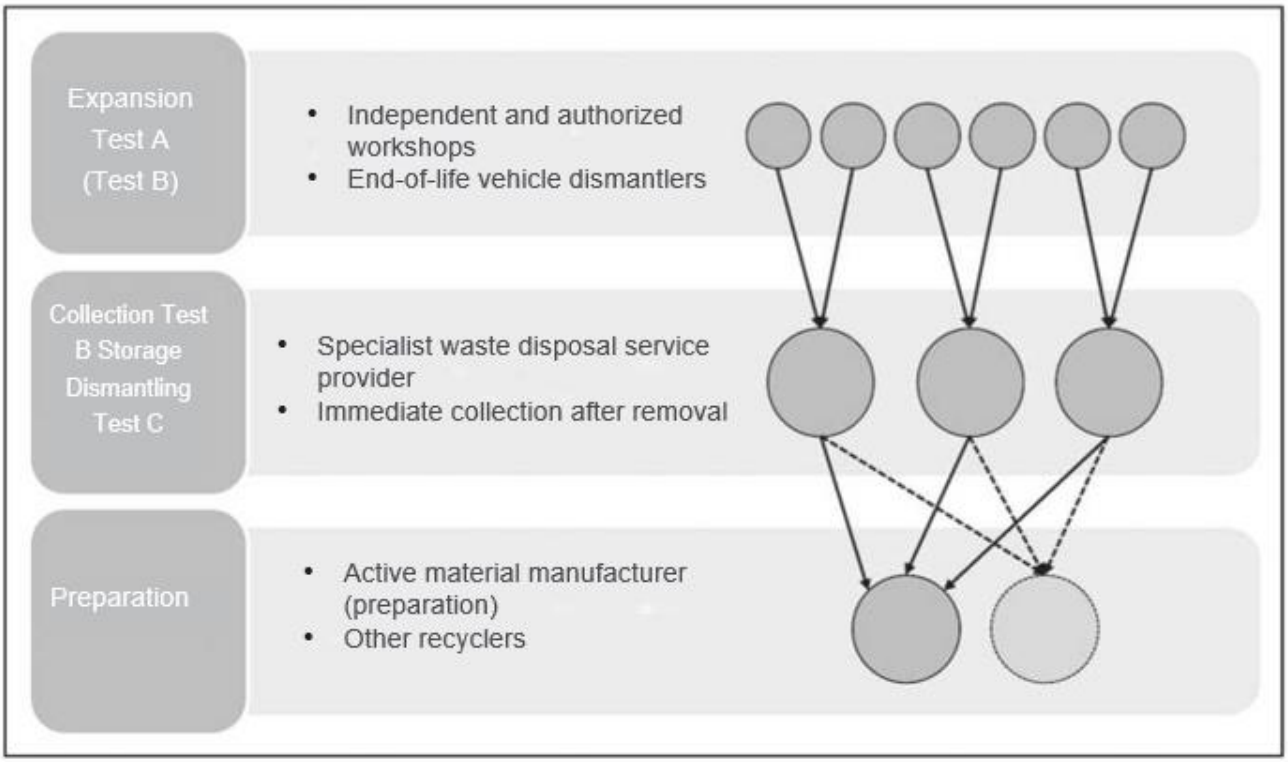


Figure A-9: Network constellation C - two-stage collection concept with decoupled dismantling and processing

A.3.1.3 Derivation of a catalog of requirements

The network-relevant activities for the collection and recycling of used lithium-ion traction batteries were identified and analyzed with regard to their possible characteristics. Based on the network constellations identified, a catalog of requirements was drawn up at network and process level (see Table A-11). This was continuously adapted to the state of knowledge during the course of the project.

Table A-11: List of requirements at network and process level and possible stakeholders

Activity	Requirements	Degree of specialization	Possible players
+: limited suitability, ++: good suitability, +++: excellent suitability			
Withdrawal	▪ Suitable devices, (measuring) tools, vehicle and electrical specialists	Medium	Authorized workshops (+++) Independent workshops (+) End-of-life vehicle dismantlers (+)
Test A	▪ Standardized system readers and automotive specialists	Low - Medium	Authorized workshops (+++) Independent workshops (+) End-of-life vehicle dismantlers (+)
Test B	▪ Standardized (BMS) readers/measuring devices and qualified electricians	Medium	Authorized workshops (+++) Independent workshops (+) End-of-life vehicle dismantling company (+) Specialist waste disposal service provider (+++)
Transport A (collection)	▪ Only undamaged batteries ▪ Dangerous goods specialists, transport vehicles, Transport container	Low	Logistics service provider (+++) Waste disposal service provider (general) (+) Specialist waste disposal service provider

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Activity	Requirements	Degree of specialization	Possible players
			(+++)
Storage	▪ Dedicated storage for batteries from vehicles ▪ Test stand (for test B), electricians, hazardous goods specialists (hazardous goods officer), storage/transport containers ▪ Connection to transport infrastructure (highway and preferably railways/waterways) ▪ Suitable storage containers for damaged batteries	High	Specialist waste disposal service provider (+++)
Transport B (bundling)	▪ Dangerous goods specialist (preferably rail or ship transport), transport container	Medium	Logistics service provider (+++) Specialist waste disposal service provider (++)
Test C Dismantling	▪ Special tools, special testing and measuring equipment, electricians, hazardous materials specialists ▪ Connection to transport infrastructure (highway and preferably railways/waterways)	High	Specialist waste disposal service provider (+++) Active material manufacturer (+)
Preparation	▪ Specialists (chemists, hazardous substance officers) ▪ Connection to transport infrastructure (highway and preferably railways/waterways) ▪ Geographical proximity to companies in the metallurgy sector, if possible also to downstream stages, e.g. cell manufacturers	High	Specialist waste disposal service provider (++) Active material manufacturer (+++)

A.3.2 Development and construction of prototype tools and design of various battery expansion concepts with the help of corresponding expansion studies

The result of the development work is a battery removal KIT suitable for the universal removal of HV batteries, which can be used in combination in six variants. Successful tests of the new development were performed on an AUDI Q5 hybrid and an Audi A6 hybrid (analogous to the A8 hybrid). This proves that it can be used both with an easily accessible HV battery in the Q5 and with a very low installation height in the trunk of the A6 and A8.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

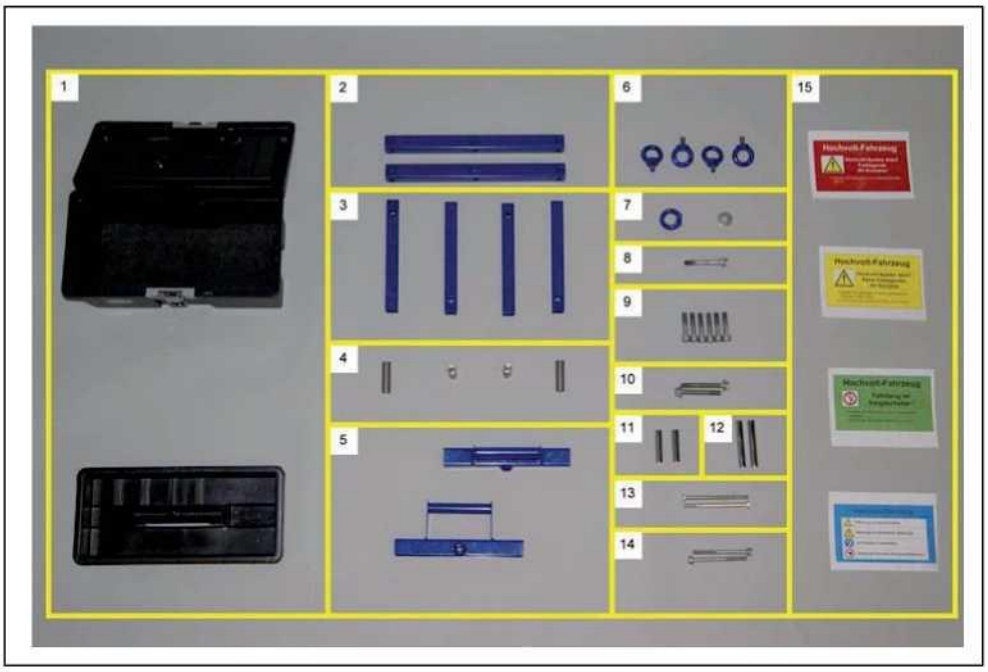


Figure A-10: HV - Battery removal KIT

The HV battery removal KIT can be used in the following assembly variants for a wide range of applications:

- Variant (1) Cross mount with screw bells - max. extension length 70 cm
- Variant (2) Carrying handle - max. distance between attachment points on battery 37.5 - 45 cm
- Variant (3) Carrying handle - max. distance between attachment points on battery 41.5 - 50 cm
- Variant (4) Single strut - max. extension length 50 cm
- Variant (5) Use of eyelets - depending on existing anchor points
- Variant (6) Cross support with screws and spacer sleeves - max. extension length 70 cm

The individual variants are described in detail in the operating instructions. The design data is shown in schematic drawings. For the use of a commercially available hydraulic workshop crane as a hoist, is used for universal application, particularly for vehicles with a very low installation height for the HV batteries (e.g. A8 and A6 hybrid) an interchangeable angled load arm for the workshop crane is recommended.

A proposal with text and photos, which can also be used as manufacturer-specific information for IDIS, has been created.

Recommendation:

- ✓ ***Even if an optimum solution for HV battery removal has been found for the AUDI models with the removal aids, consideration should be given to integrating 4 screw bells as stop aids in the on-board tool (analogous to the safety bit for wheel nuts). For the recycler who removes the HV batteries from the end-of-life vehicle and also for the manufacturer, this appears to be a cost-effective option.***

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A.3.3 Development and implementation of a packaging system and design of a fastening system

The aim of this work package was to develop a standardized but modular packaging system that could be used for different battery systems by using different base and side parts and lids.

A minimum requirement was to classify the packaging as packaging group II in accordance with packaging regulation P 903 in order to be able to transport all lithium-ion batteries with UN38.3 approval in it. However, it is currently impossible to predict the exact dimensions of the battery systems that will be produced by 2030. The container concepts presented below therefore do not refer to specific battery systems with defined dimensions, but rather define basic requirements for the containers.

Use of packaging for battery system replacement

As far as we know at present, new batteries will generally be delivered in approved disposable cardboard packaging tailored precisely to the respective battery type for cost reasons. Figure A-11 below shows an example of such cardboard packaging. The cardboard packaging fulfills the test requirements of ADR packaging group II.

Figure A-11: Disposable cardboard packaging Sanyo battery system for Audi Q5

As the average service life of the battery system is likely to be shorter than the service life of the associated vehicle, it can be assumed that a large proportion of the return quantities will be generated when the systems are replaced, meaning that approved original packaging will also be available at the point of use.

<u>Recommendation:</u>

- ✓ ***As part of this replacement process, it is recommended that service companies specify that the old battery system is to be placed in the original packaging of the replacement battery system. The batteries would then be available for the take-back process in approved packaging.***
- ✓ ***In order to make interim storage until collection and loading as safe and efficient as possible, the original packaging can also be placed in standard containers (e.g. Euro mesh boxes, Paloxes), depending on its design. This is particularly suitable for small designs (HEV).***
- ✓ ***If the original packaging is not already optimized to accommodate a pallet truck (ant), it can be assumed that the new battery system including packaging will be delivered on a pallet. Please ensure that the original packaging on the pallet is***

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

appropriately secured (e.g. with shrink wrap, plastic strapping).

Reusable container system:

Individual packaging will not always be available for take-back. Containers must therefore also be available for take-back that meet the legal requirements on the one hand and ensure environmentally friendly and cost-effective take-back on the other. Against this background, cardboard packaging is not suitable as it cannot permanently withstand the mechanical stresses of a reusable system. As a pallet system is not permitted under dangerous goods legislation, only boxes (crates) can be considered from a logistical point of view. According to subsection 6.1.2.7 ADR, the following materials may be used:

- Steel
- Aluminum
- Natural wood (simple or with dustproof walls)
- Plywood
- Wood fiber materials
- Cardboard
- Plastic (foams or rigid plastics)

An exchange of experience with waste disposal service providers revealed that steel, aluminum and rigid plastic are particularly suitable materials for a reusable container system. However, containers made of aluminum or steel are considerably more expensive than plastic containers.

Recommendation:

- ✓ ***It is recommended to use approved plastic containers of ADR packing group II for the reusable container system. The containers should be highly stable so that they can be used several times as part of the reusable system. These criteria could be met, for example, with the so-called battery box (battery box made of rigid plastic, see Figure A-12):***

Figure A-12: Battery box (battery box made of rigid plastic)

Some of the battery boxes currently on the market are type-tested in accordance with ADR and assigned to packaging group II for hazardous goods. However, the currently known type approvals do not explicitly refer to lithium-ion battery systems (UN3480), so that manufacturers must obtain appropriate proof of suitability or an adapted type approval before using this container system. If the battery systems cannot be adjusted in such a way that they do not slip

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

in the collection box due to their design, anti-slip intermediate layers must be used and any gaps filled with padding material. Due to the stable outer housing of the battery system and the protective devices of the connections (terminals), it can be assumed that the HEV (approx. 38 kg/battery) and PHEV systems (approx. 140 kg/battery) can be placed in the collection box in two layers.

A.3.4 Development and implementation of a storage system and design of a warehouse

In AS A.3.4, concepts and regulations were developed for the storage of lithium-ion batteries at dismantling facilities and workshops, collection depots and recycling facilities at the end of the disposal chain. These three sources differ significantly in terms of throughput. Workshops and dismantling sites will generally store small quantities of lithium-ion batteries, primarily for cost and space reasons. Collection and compaction warehouses will probably work with medium quantities, as the batteries are continuously forwarded to the recycling plants from an economically and logistically sensible quantity/compaction. These in turn require storage facilities for large quantities of lithium-ion batteries in order to keep the recycling process running continuously at the designed plant throughput.

As there are currently no specifications or table values in the relevant legislation for the storage of lithium-ion batteries from the automotive sector, the following must be observed when designing such storage facilities:

For the storage of lithium-ion batteries from the automotive sector without quantity restrictions, a fire protection certificate must generally be prepared by the responsible building supervisory authority or by testing experts!

Failure to do so may result in criminal prosecution and liability!

Based on the technical regulations for hazardous substances and after example consideration from the point of view of fire protection as well as consultation with battery and automobile manufacturers, recyclers and system operators for the collection of lithium-ion batteries, the following summarized minimum recommendations for requirements for the storage of lithium-ion batteries could be derived:

Structural storage requirements:

	Storage in buildings	Outdoor storage
OK batteries (new and used)	• Normal bearing	• Storage in containers at least 5 m away from buildings or other storage containers (F90 containers are recommended if the distance is less than this) • Differentiation of different storage containers through appropriate labeling • Light exterior color of the container
not OK batteries (new and used)	• Not recommended	• •After quarantine in F90 container

- Level paved floor with sufficient maneuvering space (e.g. for transport by forklift truck)
- Storage area with sufficiently large entry and exit areas (fast removal)

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- Quarantine = waiting time for possible subsequent exothermic reactions

Technical storage requirements:

- Smoke alarm with connection to the fire department (outdoors: fire alarm sensors, acoustic alarm on the container)
- Adequate fire-fighting facilities (fire extinguisher or automatic extinguishing system)
- Protection from unauthorized persons
- Ensuring a max. temperature limit < 40°C for OK batteries
- Avoidance of direct sunlight
- Sufficient ventilation devices (smoke and heat extraction openings must be dimensioned in accordance with DIN 18232-2)
- Adequate lighting inside and outside in accordance with ASR A3.4 Lighting

Organizational storage requirements:

- The storage rooms should ideally be located on external walls
- No repair work on the batteries in the storage room
- Labeling of the storage areas (hazard warnings, contact partner, representative, person responsible for the inspection)
- The employees of the respective business premises must be given special fire protection training. Fire protection regulations in accordance with DIN 14096 in parts A, B and C must be drawn up for the respective companies
- The requirements of the Workplace Ordinance must be implemented in terms of content
- Use of transport containers also as storage containers (only applies to normal storage)
- Damage to containers and packaging must be avoided at all costs. Damaged containers or packaging must be replaced immediately
- Check all storage equipment for the first time and then regularly at appropriate intervals to ensure that it functions properly, is reliable and effective, e.g:
- Compliance with shelf and bay loads of racks with storage containers or the integrity of rack parts
- Integrity of ventilation ducts and detection devices

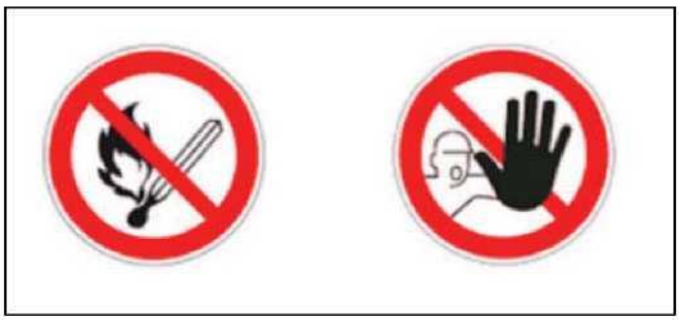


Figure A-13: Labeling of warehouse entrances and exits

A.3.5 Economic efficiency calculation of the entire collection concept

The aim of this step was to determine the costs and revenues incurred by the vehicle recycler,

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

battery recycler and Li-ion recycling company, as well as the costs/revenues for (interim) storage(s) and transportation(s).

As the majority of the data required for the calculation was not previously available (no practical experience in workshops and with vehicle/battery recyclers), an attempt was made to collect this data using similar data and empirical tests.

For this purpose, battery systems from various vehicle types of different concepts (electric/hybrid) were removed, the battery systems were further dismantled down to module/cell level and the cells were fed to a shredder in various states of charge.

The times of all these work steps were recorded in a comprehensible manner and for the individual work steps it was defined which work process required which specialist training.

Depending on the necessary specialist training, different hourly wages (on a full-cost basis) were calculated (simple employee in the dismantling plant without special training/employee with special training for work on high-voltage systems)

On this basis, vehicle-related and battery system-related battery dismantling and battery recycling personnel costs could be determined.

For the transport of non-defective ("transportable") battery systems, a price per tonne without kilometer limit was assumed analogous to the price per tonne for the collection of starter batteries.

However, the premise was established that due to the legally prescribed transport packaging for Li-ion batteries, a maximum of 8 to 9 tonnes of batteries can be transported per truck instead of 20 tonnes (as is the case for starter batteries).

For the storage costs of the batteries, 1/6 of the transport price was estimated, analogous to the price for starter battery storage - without taking the storage period into account.

This data was summarized on a spreadsheet - chronologically according to the respective process steps - and kept variable so that the costs/revenues of the respective work steps are determined depending on the vehicle and battery as well as the assumptions for wages and transport costs.

This calculation does not take into account battery systems or modules and cells that are defective and cannot be transported without further treatment. Considerations to convert the original state of the batteries/modules/cells by chemical, mechanical and/or thermal treatment into a different state, and thus possibly make them safe for transportation again, still require experimental tests and recognition by the legislator.

A further field of investigation in this work item was the determination of the costs and revenues incurred by the vehicle recycler, battery recycler and Li-ion recycling operation, as well as the costs/revenues for (intermediate) storage(s) and transportation(s).For this purpose, battery systems from various vehicle types of different concepts (electric/hybrid) were removed, the battery systems were further dismantled down to module/cell level and the cells were fed to a shredder in various states of charge.

Under these boundary conditions, vehicle-related and battery system-related battery dismantling and battery recycling personnel costs could be determined.

A value was estimated for transportation and storage based on the costs for other hazardous

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

goods. The results for transportation, storage and dismantling have been included in the results for project area PB E and in the following investigations in AS A.3.6 and AS A.3.7.

A.3.6 Development of a decision support tool for the design of networks

In AS A.3.6, the three network constellations identified in AS A.3.1 were mathematically modeled on the basis of an extended dynamic facility location problem (FLP) from AIP-TUBS. With the help of the CPLEX solver, the optimal logistical network structure in the planning horizon was determined on the basis of case studies using assumptions about the volume of used batteries and payments for the transportation, dismantling and processing of used batteries. This includes:

- Construction dates, locations and capacities of transshipment warehouses,
- Construction dates, locations and capacities of dismantling plants,
- Construction dates, locations and capacities of processing plants,
- Allocation of transport relations from sources of used batteries to the transshipment warehouses and dismantling plants (individual transports),
- Allocation of transport relations from transshipment warehouses to dismantling plants (collective transports)
- Allocation of transport relations from dismantling plants to processing plants (collective transports).

The basis for optimization is a planning horizon of several planning periods. A planning period can cover one or more years. Warehouses and plants are set up at the beginning of each planning period. The corresponding payments are also due at the same time. The useful lives of the plants are unlimited in the planning horizon. The closure of plants in subsequent planning periods is excluded. The transport relations are assigned for one planning period (see below).

Optimization is performed with the aim of maximizing the present value of the resulting annual payments. These payments include:

- payments for the construction of new transshipment warehouses and dismantling and processing plants,
- fixed annual cash operating costs (i.e. excluding imputed costs) for the operation of the constructed transshipment warehouses, dismantling facilities and processing plants,
- contribution margins proportional to capacity utilization for the treatment of batteries in the warehouses and plants (including revenues and costs for the external purchase and sale of raw materials and recyclable materials, for the disposal of residual materials and for the transport of these materials),
- material flow-related payments for the intra-system transportation of battery systems and cells.

The precondition in each case is that every battery in the network is collected and recycled (100 percent collection and treatment rate). The modeling approaches for the most important aspects of the decision problem are explained below. This concerns the model-based mapping of the geographical area, the volume of used batteries, the logistical and transformation processes, the capacities and the material flows.

A.3.6.1 Modeling the geographical area

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The discrete location planning is based on 439 districts (geographical objects, GOs) of the Federal Republic of Germany (territorial status of the Federal Republic of Germany at district level as of December 31, 2006 of the Federal Statistical Office).[7] The geographical objects form the nodes of the location planning problem and are simultaneously sources and potential transshipment storage, dismantling plant and processing locations (sinks). As part of a site preselection process, however, the potential sites are reduced to subsets. To evaluate transportation between the nodes, the average distances between the 439 circles were calculated and a mirrored distance matrix with almost 193,000 relations (edges) was formed. Due to the effort involved in manual calculation, a tool was developed that uses the route planning function of common GIS software and calculates the distance matrix automatically[8]. The routes start and end on roads near the geographical center of the circles.

A.3.6.2 Modeling the volume of used batteries

To model the sources of the used battery volume, the aggregated used battery volume was distributed by vehicle type to the 439 districts (GOs) mentioned[9]. The distribution was proportional to the number of motor vehicles at district level as of 01.01.2007 (column “Total cars”). To simplify matters, it was assumed that the ratio of cars with electrified powertrains is uniform and static throughout Germany. Regional differences are not taken into account, but the parameters can be adjusted if the data situation improves. On the source side, the volume of used batteries is broken down into HEVs, PHEVs and BEVs. To reduce complexity, the volume of the different battery types in each administrative area within the optimization is converted into so-called BEV equivalents (BEV eq.).

A.3.6.3 Modeling the processes

To map both flexible centralized and decentralized concepts of the identified network constellations A, B and C, the logistical and production-related processes of collection, handling/sorting, storage, unloading, dismantling, separation and preparation were modularized (see Figure A-14). The removal and inspection processes were not modeled, as this would require the specific modeling of all workshops and end-of-life vehicle dismantling companies. This accuracy does not appear to be appropriate, as the allocation of used battery quantities to these locations would be very problematic. It also drastically increases the complexity of the modeling

[7]Although more recent data from the Federal Statistical Office is available, it is not compatible with the software used to calculate the distances due to the district reforms in recent years.
[8]The application was developed in Microsoft C# and uses the programming interface of Microsoft MapPoint Europe 2010
[9]The annual aggregated waste battery volume at federal level in the years 2010 to 2050 (results of **AP A.1**).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

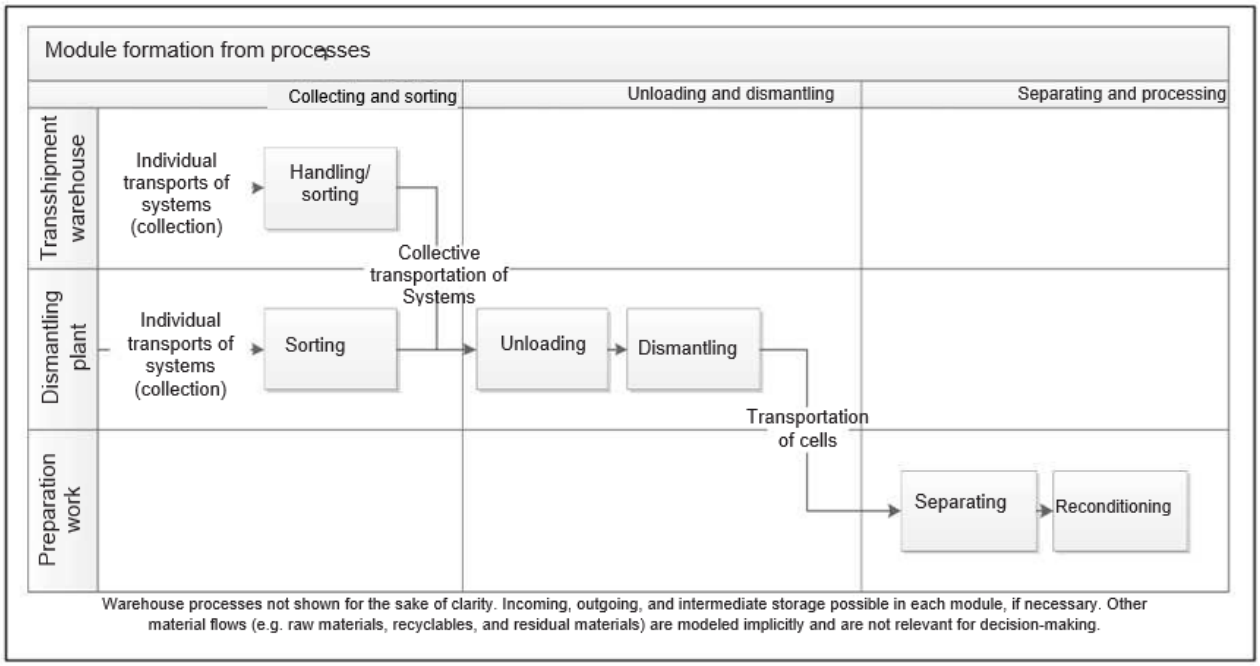


Figure A-14: Module formation from processes.

The *collection*, *handling/sorting* and *storage* processes take place in the transshipment warehouse module. This optional module is primarily used to consolidate transports in order to exploit economies of scale. Waste batteries are collected in individual shipments from the sources of the waste battery volume, stored for a short time if necessary and transported to dismantling plants in bundles and as sorted as possible. The term “transshipment warehouse” makes it clear that the logistical process of storage is not excluded, but is not the main focus. The mandatory dismantling plant module is a handling module extended to include the subsequent *unloading* and *dismantling* processes. Used batteries can therefore be collected directly from the sources as well as delivered from the transshipment centers. After short-term storage, if necessary, the old battery systems are discharged as far as possible and dismantled down to cell level. The cells are then discharged again. With the exception of the cells, the individual fractions (e.g. steel and plastic housings, copper cables, BMS) are fed into the (locally) existing recycling structures. Corresponding transports are assumed to be irrelevant to the decision and are therefore not explicitly modeled, but are included in the monetary valuation on a flat-rate basis. The cells are delivered to the processing plant module, which combines the technical processes for recovering the active material components, *separation* and *processing*.

In a single-stage collection concept (constellation A), the dismantling warehouse and processing plant modules are combined in one location. If only one dismantling warehouse and one processing plant are opened, this is equivalent to a centralized collection concept; if several such combinations are opened, this is a decentralized collection concept. In the two-stage collection concept with integrated dismantling and reprocessing (constellation B), at least one - spatially separated - transshipment warehouse is located in front of at least one dismantling plant. However, dismantling and processing plants are generally combined locally. In contrast, in the two-stage collection concept with decoupled dismantling and reprocessing (network constellation C), at least one dismantling plant is physically separated from a reprocessing plant. This requires the spatial decoupling of dismantling and reprocessing and the possibility of transporting discharged cells.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A.3.6.4 Modeling of capacities

Different capacities can be mapped across any number of capacity classes for the three modules.[10] For each module-related capacity class, maximum processing capacities per planning period, specific investment payments for the construction of a module, fixed payments (cash-equivalent fixed costs) per planning period for the operation of a module and variable payments (cash-equivalent contribution margins) per processed unit in the module are defined. The capacity of a transshipment facility thus corresponds to the maximum transshipment capacity [BEV-eq./planning period] (not the maximum storage capacity), the capacity of dismantling plants corresponds to the maximum dismantling capacity [BEV-eq./planning period], the capacity of processing plants corresponds to the maximum processable cell mass [t cells/planning period]. At the beginning of each planning period, several transshipment warehouses or plants of different capacity classes can be opened at a given number of potential locations.

A.3.6.5 Modeling of material flows

The material flows between sources, transshipment facilities and dismantling plants are mapped in BEV equivalents. The transport relations between the sources and sinks are controlled through corresponding decision variables. The allocation of a source to transshipment warehouses and dismantling plants is unique for each planning period, so it is not possible to allocate it to different plants. Intertemporally, however, this allocation is dynamic in order to do justice to the short-term operational nature of transportation planning.

The general cargo transports between sources on the one hand and transshipment warehouses and dismantling plants on the other are valued on each route in proportion to distance and volume using a uniform individual transport cost rate [EUR/(km*BEV-eq.)] standardized to BEV equivalents. The average capacity and utilization of the transport vehicles can therefore be implicitly performed by determining the individual transport cost rate. The allocation of the collective transports of a transshipment facility to a dismantling plant and those of a dismantling plant to processing plants are ambiguous. This means that the batteries collected in a transshipment warehouse can be delivered to different dismantling plants and the cells separated in a dismantling plant can be delivered to different processing plants. The collective transports between transshipment warehouses and dismantling plants (stage 1) are valued in proportion to distance and volume using a uniform collective transport cost rate for the transportation of a BEV equivalent [EUR/(km*BEV eq.)]. Due to transport bundling and higher capacities in collective transport, the collective transport cost rate is set considerably lower than the individual transport cost rate.

The transformative dismantling processes in the dismantling plant are mapped using an input-output model. Battery systems (in BEV equivalents) are therefore included in the dismantling plant. Finding the way out of dismantling and into reprocessing

Battery cells in metric tonnes (t), the conversion is performed using transformation coefficients. The collective transports between dismantling and processing plants are valued in proportion to distance and mass using a uniform material transport cost rate for the transportation of one tonne of cell material [EUR/(km*kg)].

[10] However, the number of mapped capacity classes has a strong influence on the solution effort.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A.3.7 Deriving recommendations for action to design the network structure

In work step AS A.3.7, AIP-TUBS developed various case studies, each of which investigated different issues relating to the design of the network structure with the help of the mathematical model developed in AS A.3.6. The respective parameterization of the case studies is divided into a cross-case study parameterization and a case study-specific parameterization, which are first explained below. Some of the case studies developed and their results are then presented.

Cross-case study parameterization

The sources of waste batteries correspond to the above 439 administrative regions (VG) of the Federal Republic of Germany. The transportation distances are also the same for all case studies. Identical assumptions are made with regard to the battery types (standardization with regard to the evaluation of the transports and the capacity coefficients in transshipment warehouses and dismantling plants, transformation coefficients, see Annex 5) and the transport costs (see Annex 6). Furthermore, the maximum catchment area of transshipment centers and dismantling plants for the collection of batteries is limited in order to reduce the solution effort and exclude unrealistic solutions. The catchment area is set at 654 km in the model (this corresponds to the maximum distance from the administrative area of the city of Kassel to all other VGs). Lower values would mean that at least two locations would be required for collection, regardless of the volume. Common to all case studies is the average discount rate of 9 percent per year, which is used to discount the future annual payments.

The planning horizon of the case studies is limited to the years 2012 to 2025 inclusive (11 years) and divided into four planning periods of different durations. Planning periods I, II and III each cover three years (2012-2014; 2015-2017; 2018-2020), planning period IV covers four years (2021-2025).

Case study-specific parameterization

For each case study, it is possible to set which scenario for the volume of used batteries (Pessimistic, Political and Realistic scenarios, see AP A.1) is to be taken into account in the optimization. In the case of robust optimization, several scenarios can be selected simultaneously. The scenario-related probability of occurrence can be defined for this purpose. For each study, the number of potential locations for transshipment warehouses, dismantling plants and processing plants can be specified. For this purpose, two study-specific data sets can be used, which were created as follows:

(1) VG-10 locations: The number of potential locations is limited on the basis of a “weighted regional volume” indicator. The key figure sets the volume of surrounding administrative areas in relation to the distance to these administrative areas. In turn, 10 administrative areas with a high weighted volume are selected from the list sorted according to the key figure. This quantity is supplemented by the Kassel and Goslar locations in order to be able to map both centralized and decentralized network constellations.

(2) VW OTLG locations: A potential location is any administrative area in which a location of “Volkwagen Original Teile Logistik” (VW OTLG) is located, and Goslar. This results in a total of 8 potential locations: Darmstadt-Dieburg, Goslar, Kassel district,

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Cologne, Ludwigsburg, Munich city, Segeberg and Teltow-Fläming.

The location for a processing plant is limited to the district of Goslar. There is already a pilot plant for hydrometallurgical processing operated by Chemetall in this district; opening a second plant at a further location does not appear worthwhile for the time being due to the high investments involved and the high level of uncertainty regarding the volume. The limitation also results in a significant reduction in the solution effort. In order to be able to depict network constellation B with integrated dismantling and processing, the two site quantities also include the district of Goslar.

Case study-specific capacity classes and class-specific payments can also be specified. Over time, the payments associated with transshipment warehouses, dismantling plants and processing plants of different capacity classes were specified in feedback with the results from project area E (see Annex 7, non-decision-relevant values in brackets). The capacity classes available for selection in a study can be limited to a subset.

Interpretation of the results

The studies presented below are expressly not intended to assess the economic viability of lithium-ion battery recycling (corresponding investigations are being performed in project area E), but to evaluate the network alternatives developed. The capital values calculated in the optimization model presented do not reflect the values actually realized in the future. In this way, possible alternative uses of the assets under review and thus cash flows from other business activities are eliminated. Alternative options for the return and disposal of used batteries, which would be considered in the case of extremely small quantities, are also neglected.

A.3.7.1 Political/VW-OTLG case study

In the “Political/VW-OTLG” case study, the structure of a network is examined in which the existing structures of the VW-OTLG network are used and which is geared towards the realization of the used battery volume at the level of the “Political” scenario. Due to the high volume in this scenario, sufficient capacity is provided in this network to be able to process all batteries at any time, even if the “Realistic” or “Pessimistic” scenario is realized. The case study shows the optimality of network constellation C with initially centralized and later decentralized collection. Dismantling and processing are performed locally decoupled.

Annex 8 compares the annual capacities for dismantling and reprocessing built up in the planning period with the annual volume of spent batteries. It is clear that the capacity expansions in processing in particular could be performed at a later date. On the other hand, it should be reviewed in due course whether a larger capacity plant should be built to take advantage of economies of scale instead of the five plants built during the planning period, each with an annual capacity of 8,000 tonnes of cells. However, these decisions do not influence the investigation of the optimal network structure, which is the main focus here. The site openings and the capacities maintained over time are explained period by period below.

In the first planning period from 2012 to the end of 2014, the small volume of waste generated throughout Germany will be collected and processed centrally by a small-capacity dismantling plant set up in the VG Landkreis Kassel. From there, the cells are transported to the processing plant in Goslar. The processing capacity therefore amounts to 14.400 BEV equivalents with a volume of a good 900 BEV equivalents in the planning period of three years.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

In the second planning period from 2015 to the end of 2017, the network structure will change to decentralized collection. A newly built small dismantling plant in Goslar takes over the collection in northern and eastern Germany. The part of Germany south of the Main and Moselle rivers is served by a new small transshipment warehouse in Ludwigsburg, and the batteries collected there are divided between the two dismantling plants in Kassel and Goslar. The catchment area of the existing Kassel dismantling plant will be reduced to the center of Germany. The network's dismantling capacity in the planning period is now 28.800 BEV equivalents, compared with around 11.200 BEV equivalents (approx. 39% capacity utilization). The geographical representation in Figure A-15 shows the basic structure of the network in the planning period. The figure shows the individual transport flows (star-shaped gray lines), the flows of collective transports from transshipment warehouses to dismantling plants (green curved arrows) and the cell transport flows (red arrow). For the sake of clarity, the flows between two locations are only shown as the crow flies. The line thicknesses indicate the extent of the flows in comparison to the following diagrams.

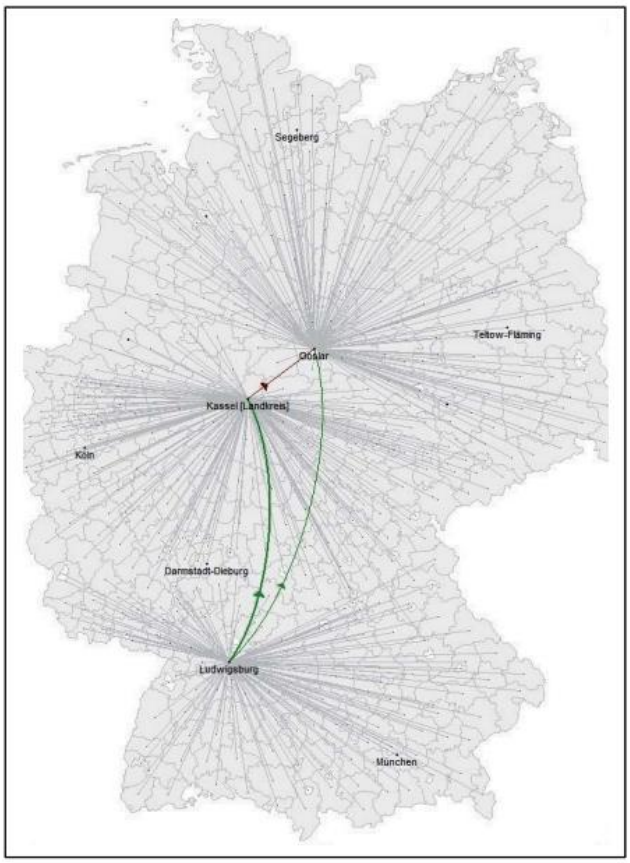


Figure A-15: decentralized collection in the "Political/VW-OTLG" case study, second planning period 2015 to the end of 2017

In the third planning period from 2018 to the end of 2020, two further small transshipment warehouses will be built in Cologne and Teltow-Fläming and a large dismantling plant in Darmstadt-Dieburg. The six collection points are now assigned to correspondingly smaller catchment areas (see Figure A-16). The dismantling capacities in the network will increase to 144,000 BEV equivalents in the planning period, the volume to a good 95,000 BEV equivalents (utilization 66 percent). In order to be able to process the 19,000 tonnes of cells in the planning period, the existing processing capacity will be increased to 48,000 tonnes of cells.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

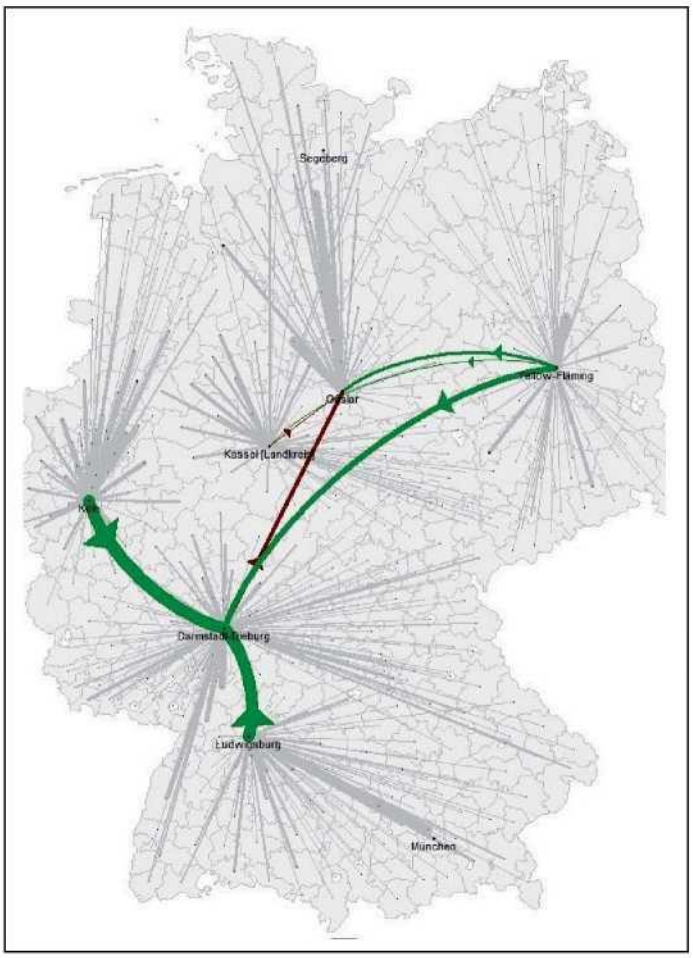


Figure A-16: decentralized collection in the "Political/VW-OTLG" case study, third planning period 2018 to the end of 2020

The enormous increase in volume in the longer fourth planning period from 2021 to the end of 2025 will lead to the construction of a further small transshipment facility in Kassel and four further large dismantling plants in Segeberg, Cologne, Munich and Teltow-Fläming. The resulting network is characterized by a highly decentralized collection and dismantling of batteries: ninety percent of the batteries are collected and processed directly by the seven dismantling plants; only ten percent of the batteries are previously collected in transshipment warehouses. The structure is illustrated in Figure A-17. With a volume of around 570,000 BEV equivalents in the planning period, the dismantling capacities amount to a good 1 million BEV equivalents and the processing capacities to 200,000 tonnes of cells (capacity utilization approx. 57 percent).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

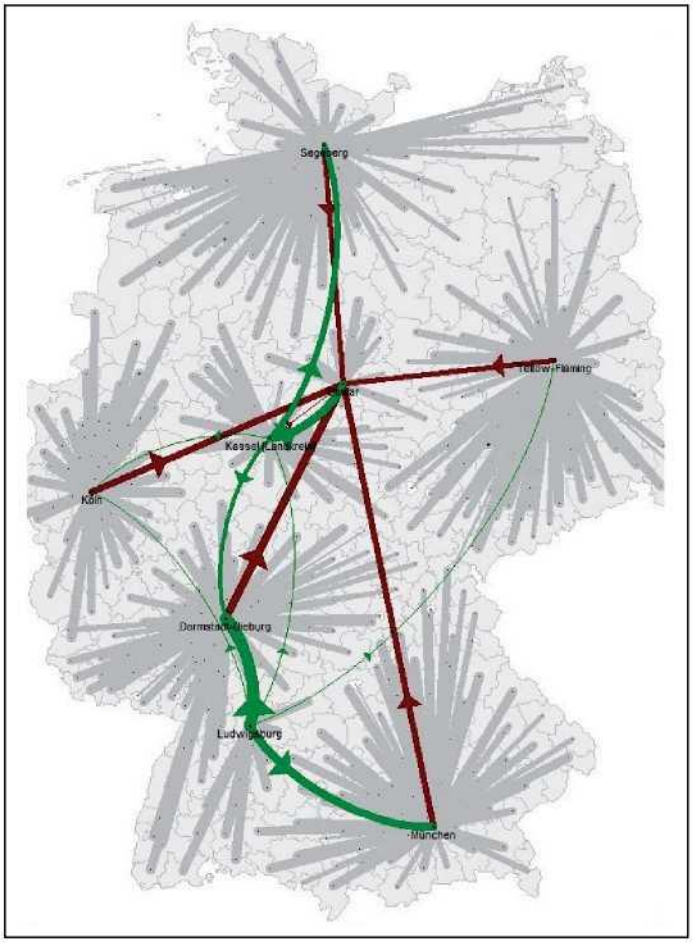


Figure A-17: Highly decentralized collection and dismantling in the "Political/VW-OTLG" case study, fourth planning period 2021 to the end of 2025

A.3.7.2 Realistic/VW-OTLG case study

In the "Realistic/VW-OTLG" case study, the structure of a network is examined that is geared towards the realization of the used battery volume at the level of the "Realistic" scenario. Due to the lower volume in this scenario, this network may not provide sufficient capacity to process all batteries at all times, even if the "Political" or "Pessimistic" scenario is realized. The case study shows the optimality of network constellation C with initially centralized and later decentralized collection and dismantling. Dismantling and processing are performed locally decoupled.

In the first planning period from 2012 to the end of 2014, the small volume of waste generated throughout Germany will be collected and processed centrally by a small-capacity dismantling plant set up in the district of Kassel. From there, the cells are transported to the processing plant in Goslar. The total processing capacity is 14.400 BEV equivalents with a volume of only 60 BEV equivalents in the planning period.

In the second planning period from 2015 to the end of 2017, the network structure of the first planning period will be retained.

In line with the sharp rise in the volume of used batteries, a fully decentralized collection and

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

dismantling concept is optimal from the fourth planning period from 2021 to the end of 2025. In addition to the existing site in Kassel, four small dismantling plants will be set up in Segeberg, Cologne, Darmstadt-Dieburg and Munich. In total, dismantling capacities of 120,000 BEV equivalents with a volume of approx. 65.600 BEV equivalents will be available in the planning period. The processing plant will be operating at one third of its capacity in the planning period with approx. 13.100 tonnes of cells to be processed.

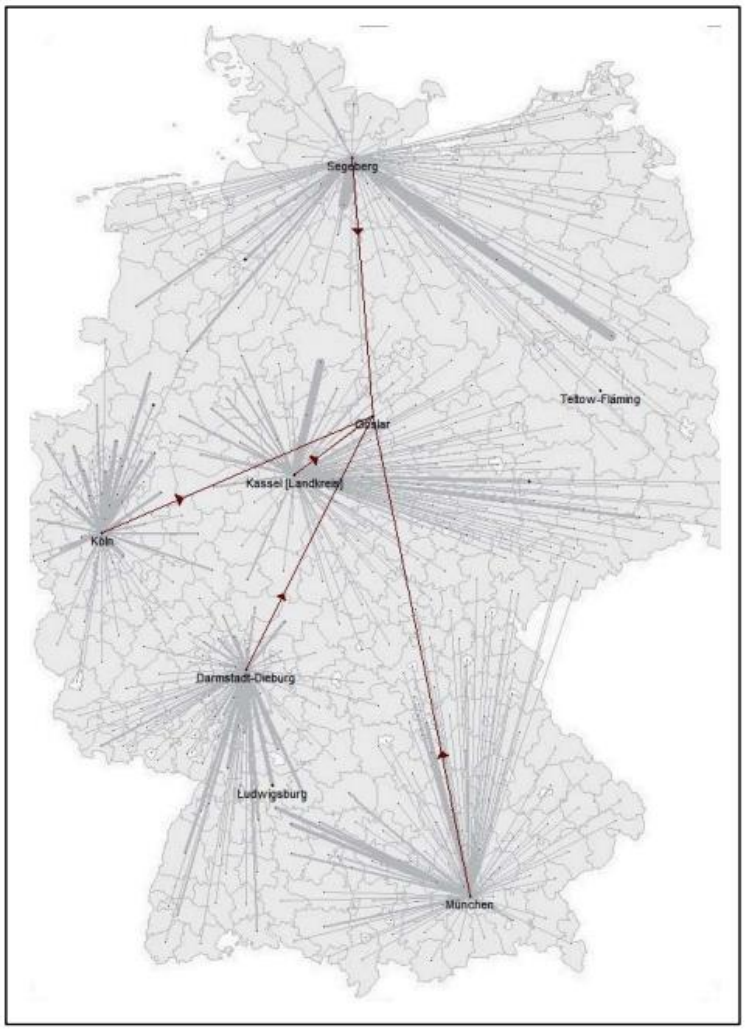


Figure A-18: decentralized collection and dismantling in the "Realistic/VW-OTLG" case study from 2021 to the end of 2025

A.3.7.3 Realistic/VG-10 case study

In the case studies shown above, the selection of potential locations for transshipment warehouses and dismantling plants is limited to VW OTLG locations. Reducing the number of potential locations offers the advantage of being able to incorporate an already established logistics structure into the planning. On the other hand, the reduction potentially excludes sensible and cost-reducing locations. The "Realistic/VG-10" case study therefore examines the extent to which deviations occur in the network structure when the number of potential locations changes. The quantity available for selection is set to the data set "VG10" (locations with a high regional volume). As a result, there are only minimal deviations and the structure remains the same throughout the entire planning horizon: collection and dismantling are performed decentrally from the fourth planning period onwards (network constellation C). The case study leads to a higher net present value (+0.8 percent) in the period under review from

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

2012 to the end of 2025. This slight improvement is due to a 5% saving in transportation costs, which is mainly due to the location of the sites in Hamburg (compared to Segeberg) and the Rhine-Neckar district (compared to Darmstadt-Dieburg). However, it should be put into perspective in that the transportation costs saved, particularly in the case of the Hamburg location, could be offset or even exceeded by higher location costs not considered here. In the event of a precise location decision at local level, the Segeberg site or another administrative area outside Hamburg would probably be preferred for practical reasons. Annex 9 compares the structures of the networks of the two case studies in the fourth planning period.

A.3.7.4 Robust/VW-OTLG case study

In the “Robust/VW-OTLG” case study, the network structure is sought which, taking into account all three scenarios for the volume of used batteries, is permissible for a given probability of occurrence and maximizes the expected net present value. This network structure can be called “robust” if it still leads to permissible and relatively good solutions when one of the scenarios is actually realized. The total installed capacity per planning horizon is based on the scenario with the highest volume. The probabilities of occurrence of the scenarios are determined as follows: Pessimistic scenario 20%, Political scenario 30%, Realistic scenario 50%.

As a result, the robust network structure shows great similarities to the network structure optimized for the “Political” scenario. As in the other case studies, centralized collection and dismantling is optimal in the first planning period. As in the “Political/VW-OTLG” case study, decentralized collection and dismantling becomes advantageous from the second planning period onwards. The main difference in the robust structure of periods II to IV compared to the structure of the “Political/VW-OTLG” case study lies in the following aspects:

- Planning period II: The small dismantling plant is built in Teltow-Fläming (instead of Goslar).
- Planning period III: The small transshipment warehouse is built in Segeberg (instead of Teltow-Fläming). The transshipment warehouse in Cologne is no longer required.
- Planning period IV: The large dismantling plant is built in Goslar (instead of Segeberg). The transshipment warehouse in Goslar is no longer required.

The differences in the network structures are shown geographically in Figure A-19 for period III and in Figure A-20 for period IV. The net present values of the robust solution as a function of the scenario that occurs are compared in Table A-12 with the normalized net present values achieved with scenario-specific optimization. For the “Realistic” scenario, it becomes clear that the robust solution leads to an enormous deterioration compared to the scenario-specific optimization. This is due to the fact that the total installed capacity is specified by the “Political” scenario in order to achieve the 100% collection and treatment rate

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

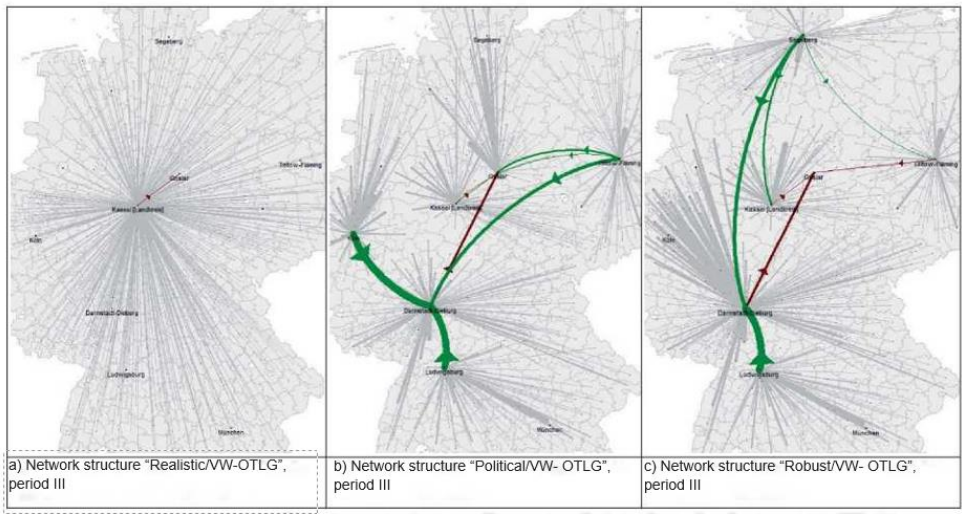


Figure A-19: Comparison of the structures in period III from the case studies “Realistic/VW-OTLG” (a) and “Political/VW-OTLG” (b) with those from the case study “Robust/VW-OTLG” (c)

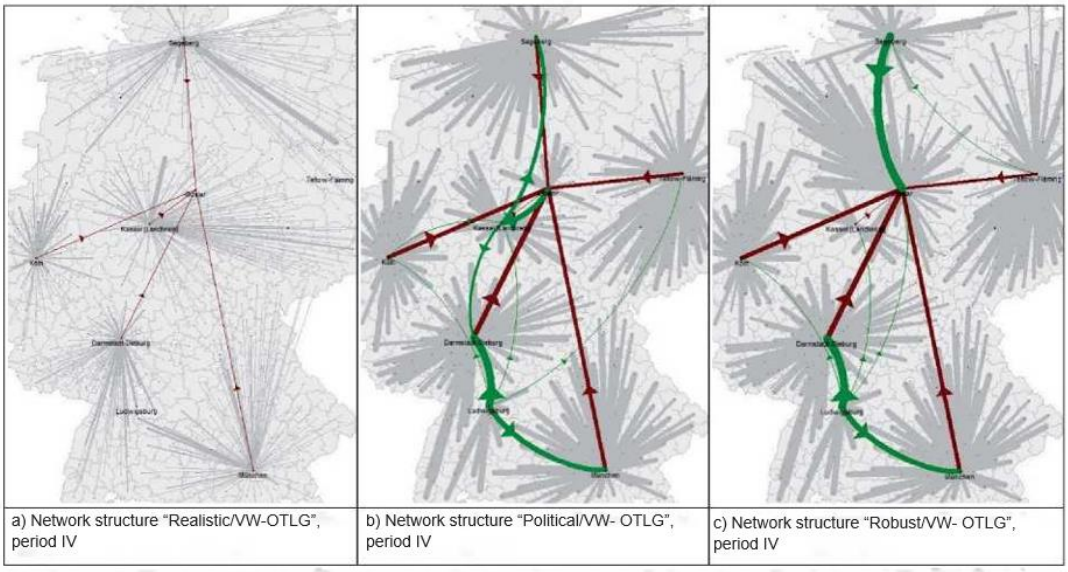


Figure A-20: Comparison of the structures in period IV from the case studies “Realistic/VW-OTLG” (a) and “Political/VW-OTLG” (b) with those from the case study “Robust/VW-OTLG” (c)

Table A-12: Comparison of net present values in scenario-specific and robust optimization

	Net present value scenario optimization [normalized]	Change Robust optimization [normalized]
Realistic	100 %	-59 %
Political	100 %	-3 %

A.3.7.5 Deriving recommendations for action

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Cross-manufacturer recycling network

For the first period, the construction of an initial dismantling plant in the order of up to 5,000 BEV equivalents/year in the immediate vicinity of the processing plant is recommended: Both the scenario-specific case studies and the “Robust/VW- OTLG” case study indicate that a **centralized single-stage collection concept** (network constellation A) should be aimed for during the first planning period (2012 to the end of 2014). All batteries are transported to a centrally located dismantling plant where they are dismantled down to cell level. The cells are then also sent to a central processing facility.

The benefits of expanding the network in subsequent periods depend heavily on the volume of used batteries realized. If only a low volume similar to the “Realistic” scenario occurs, **the central single-stage collection and dismantling concept** remains optimal up to and including the third period. If, on the other hand, a similarly high volume of used batteries is registered as in the “Political” scenario, a transition to decentralized two-stage collection and dismantling (network constellation C) is recommended. In the second period (2015 to the end of 2017), a second dismantling plant in the same order of magnitude of 5,000 BEV equivalents per year will be necessary; in addition, a transshipment warehouse located in southwest Germany should be built. In the third period (2018 to the end of 2020), a large dismantling plant (approx. 40,000 BEV equivalents/year) and an expansion of the processing plant would be necessary for the first time.

In the fourth planning period (2021 to the end of 2025), all case studies show that decentralized collection and dismantling is optimal, so that this should be the long-term goal. The structures of the “Realistic/VW-OTLG” and “Political/VW-OTLG” case studies are very similar with regard to the dismantling plant locations. In both case studies, plants are being built in Kassel, Segeberg, Cologne, Darmstadt-Dieburg and Munich. In the “Political/VW-OTLG” case study, however, the majority of these are assigned to the size class up to approx. 40,000 BEV equivalents and are supplemented by plants in Teltow-Fläming and Goslar as well as several transshipment warehouses. In both the “Realistic/VW- OTLG” and “Realistic/VG-10” case studies, on the other hand, there are network constellations without transshipment warehouses in which both collection and dismantling of the batteries are performed decentrally by several dismantling plants.

Obstacles to cross-manufacturer collection and treatment

From an economic perspective, the cross-manufacturer collection and treatment of traction batteries is the preferred solution, as it allows economies of scale[11] to be exploited and the investment risk for the individual player is lowest due to risk aggregation. However, a comprehensive solution faces various obstacles from the individual car manufacturers:

(1) The operation of a comprehensive network requires long-term contracts and coordination between direct competitors.

(2) Cross-manufacturer collection and dismantling is accompanied by allocation problems with regard to the costs incurred and the revenue generated.

(3) The reuse of components in the production of new or refurbished batteries could possibly argue in favor of dismantling near the production sites of a manufacturer and against cross-manufacturer dismantling.

(4) In the case of cross-manufacturer dismantling, competitors could possibly gain direct

[11] Falling average costs due to fixed cost degression, learning processes and economies of scale.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

access to confidential technical information about batteries, e.g. long-term performance statistics.

Obstacles 1 and 2 could be mitigated by the manufacturers setting up a joint venture and entrusting it with the task of collection, dismantling and reprocessing. The billing system for running costs could be based on the system of the “Stiftung Gemeinsames Rücknahmesystem Batterien”.[12] However, financing the initial investment in dismantling and reprocessing plants appears to be more problematic if this is to be divided “fairly” between manufacturers of different sizes. Difficulties arise above all in estimating the expected volume of used batteries from the individual manufacturers.

If a local concentration of production and dismantling is preferred (obstacle 3), the collection and sorting of batteries could be performed across manufacturers, but dismantling could be performed on a manufacturer-specific basis. In this case, the car manufacturers producing in Germany would take over the collection for an area around their production site for all cooperating companies, then sort the batteries by manufacturer and hand them over to them in collection transports. In order to eliminate obstacle 4, however, sorting and collection would have to be performed in transshipment warehouses by joint ventures; in contrast, the individual manufacturer would not come into direct possession of the batteries of other manufacturers. However, the assessment of the advantages of the two concepts requires a more detailed methodological examination.

Irrespective of the obstacles mentioned, cross-manufacturer reprocessing appears to be advantageous in all aspects, at least if the LithoRec process is ecologically and economically superior to other processes.

Influence of legal regulations and achievable collection rates

In the case studies considered, it was assumed in each case that all waste batteries are returned and thus actually end up in the hands of the car manufacturers. Deviations in the collection rates were only implicitly taken into account by considering scenarios with different volumes. However, experience from other recycling networks (e.g. end-of-life vehicle recycling) shows that these 100% collection rates cannot always be met, as a significant proportion of the products to be collected often leave the system. In general, this share is estimated to be low in the case of traction batteries and results, for example, from the resale of electric vehicles or their batteries to areas outside the scope of the relevant legislation, from retention by owners or from the purchase and reuse of batteries from third parties.

The legal obligation for manufacturers to take back and recycle waste means that significant investments in high-performance recycling networks are necessary. In view of this, it is very important to ensure that as many of the aged batteries as possible remain in the system so that they can find their way into the networks. Corresponding measures could include direct incentives such as deposit systems, contractual obligations, alternative business models or statutory export restrictions. Whether the use of such measures is necessary in the case of traction batteries, the effectiveness and efficiency of the individual measures and how the measures are to be designed appropriately must be investigated in further research projects.

[12]This involves allocating the total costs of recycling portable batteries to a participating battery manufacturer based on the quantity of batteries it has placed on the market in previous years. Due to the expected better data situation, such an estimate would not be necessary for the case of traction batteries.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A.4 Development of discharge processes for Li-ion batteries

A.4.1 Researching secondary markets for lithium-ion battery modules

Possible secondary markets for the use of used lithium-ion battery modules are shown in Figure A-21, broken down by market volume and market potential.[13]

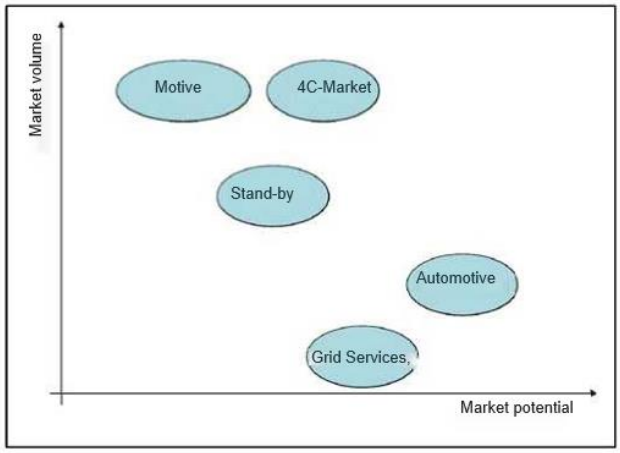


Figure A-21: Secondary markets

An application portfolio exists for each market, on the basis of which the technical requirements are determined in AS A.4.2. Some examples are shown in Table A-13.

Table A-13: Applications in secondary markets

4C-Market	Motive	Automotive	Stand-by	Grid services
Portable devices	Industrial trucks	Starter battery	Uninterruptible power supply	Peak shaving
Consumer electronics	Automated guided vehicles	Battery for a fully electric vehicle	Emergency power generators	Load shifting
	Forklift truck	Hybrid battery	Starter batteries for diesel generators	Electricity trading

The condition of used batteries is compared with the technical requirements determined in AS A.4.2 in order to check the suitability of the batteries for the individual applications.

A.4.2 Preparation of technical specifications for the secondary markets

The areas of application for battery modules and systems were identified in **AS A.4.1**. In **AS A.4.2**, the requirements for battery systems were determined for the various applications using a catalog of criteria. To this end, the criteria catalog was distributed to the project partners and discussed with them.

[13] Vgl. (Takeshita, 2009).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Furthermore, the criteria were weighted for each application in consultation with the project partners. This is necessary because gravimetric energy and power density are particularly important for mobile applications. In stationary applications, however, these criteria are less important.
This information can now be used to determine the suitability of a battery system for the various applications using an evaluation model. As the condition of the returning battery systems is not known at the present time, an estimate is made of the expected properties. The characteristics of the criteria shown in Table A-14 are assumed:

Table A-14: Cell parameters

	Energy density [Wh/kg]	Power density [W/kg]	Efficiency [%]	Reliability [0-10]	Capacity throughput/cell [kWh]	Price [€/kWh]
Cell parameters	70	500	70	7	34.98	70

These assumptions correspond to a capacity of 50% of a new lithium-ion battery. If these assumptions are compared with the weighted requirements in the evaluation model, the result is the suitability of the system for the various applications shown in Table A-15:

Table A-15: Suitability of the battery system for the identified applications

	Market	Suitability Li-Ion EoL
Motive	Industrial trucks	8.18
	Automated guided vehicle systems	7.67
	Small attraction	7.76
Automotive	Starter battery	7.23
	Hybrid vehicles	6.21
	Fully electric	5.61
Stand-by	IT/Telecom	8.30
	UPS	7.79
	(Nuclear) power plants	7.48
	Safety lighting	7.68
	Signaling systems	8.53
	Diesel start	7.54
	Solar	8.35

Suitability is shown on a scale of 0-10, with 10 indicating complete suitability for the application.

A.4.3 Analysis of existing battery modules with regard to the depth of repair

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

In AS A.4.3, current battery systems are examined to determine whether a repair is possible if an individual component fails. To do this, it is necessary to be able to identify the defective component. These usually comprise a housing, the power electronics, several cell connectors, several sub-modules and several individual cells. Each of these components has its own probability of failure. The repair depth of a battery system indicates whether it is possible to replace a component without damaging other components and whether the remaining components can be dismantled without causing damage. The results of the analysis are shown in Table A-16, Table A-17 and Table A-18.

Table A-16: Depth of repair battery system A

		Reuse					
		Housing	Power electronics	Cell connector	Module	Cell composite	Single cell
Failure	Housing	no	no	no	yes	no	no
	Power electronics	yes	no	yes	yes	yes	yes
	Cell connector	yes	no	no	no	no	no
	Module	yes	yes	yes	no	yes	yes
	Cell composite	no	yes	no	no	no	no
	Single cell	no	yes	no	yes	no	no

For example, it is not possible for battery system A to replace the cell connectors if they are defective and to reuse the repaired module. Overall, this system has several connections that cannot be released non-destructively. Furthermore, there is no standardized access to the individual cell voltages.

Table A-17: Depth of repair battery system B

		Reuse					
		Housing	Power electronics	Cell connector	Module	Cell composite	Single cell
Failure	Housing	no	yes	yes	yes	yes	yes
	Power electronics	yes	no	yes	yes	yes	yes
	Cell connector	yes	yes	no	yes	yes	yes
	Module	yes	yes	yes	no	no	yes
	Cell composite	yes	yes	yes	yes	no	yes
	Single cell	yes	yes	yes	yes	no	no

Battery system B has no non-detachable connections, which is why the majority of the components can be replaced or the remaining components can be reused.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Table A-18: Repair depth of battery system C

	Reuse						
		Housing	Power electronics	Cell connector	Module	Cell composite	Single cell
Failure	Housing	no	yes	no	yes	yes	yes
	Power electronics	yes	no	yes	yes	yes	yes
	Cell connector	no	yes	no	yes	yes	yes
	Module	yes	yes	yes	no	no	yes
	Cell composite	yes	yes	yes	yes	no	yes
	Single cell	yes	yes	no	yes	no	no

The dismantling times and costs were recorded in PB B.

A.4.4 Development of an evaluation methodology for battery modules and single cells

The aim of **AS A.4.4** is to develop an evaluation methodology that allows two successive decisions. The first step is to check whether there is a repairable defect in the faulty battery system. In this case, the depth and cost of the repair will be used to determine whether the defect will be repaired or whether the battery system will be sent for material recycling. The analysis of the depth of repair has shown that only minor mechanical defects or (software) errors in the BMS can be rectified at the current stage of development. These defects are most effectively identified with the help of the BMS functionalities and the corresponding error codes.

The following obstacles can occur when evaluating using BMS functionalities:

- Unknown error codes and interfaces (standardization)
- No functionality of the BMS outside the vehicle (technology)

To circumvent these obstacles, an adapter was developed in **AS A.4.5** to enable battery systems to be read out and evaluated using a commercially available diagnostic PC in a dismantled state.

According to the current state of the art, the following data of the individual cells in the hybrid vehicles of Audi AG are relevant to service life:

- Capacity of the individual cells
- Internal resistance of the individual cells in charging direction
- Internal resistance of the individual cells in discharge direction

Some of this data can be read from the battery management system.

The following evaluation methodology is applicable for cell and module evaluation:

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A corresponding evaluation methodology in graphical form is shown in Figure A-22.

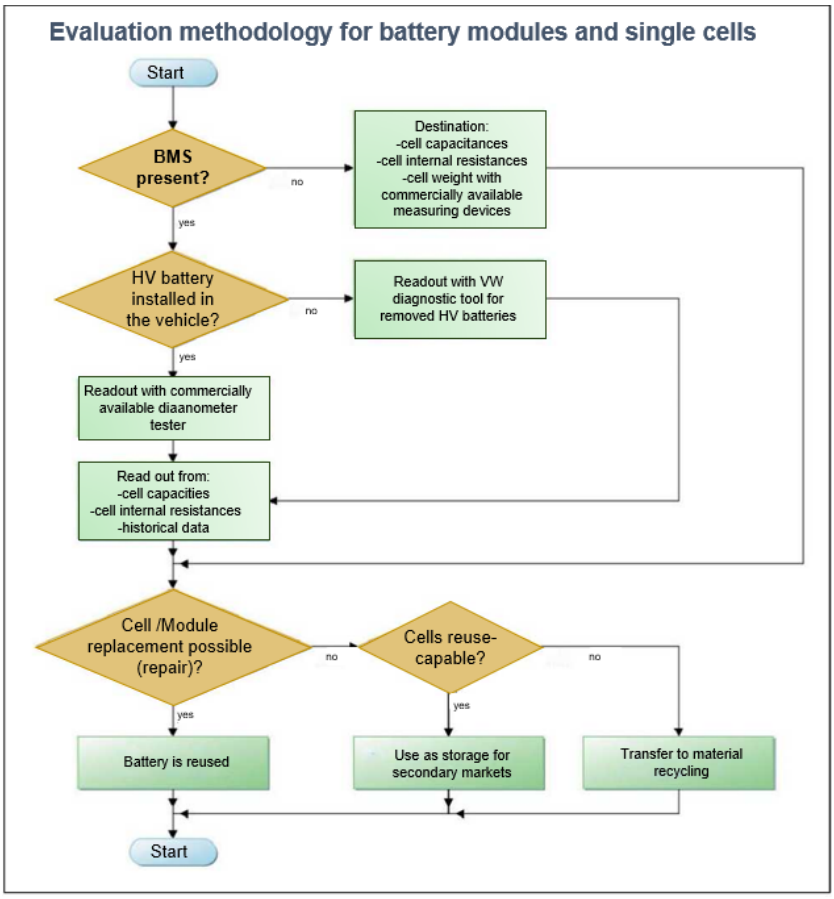
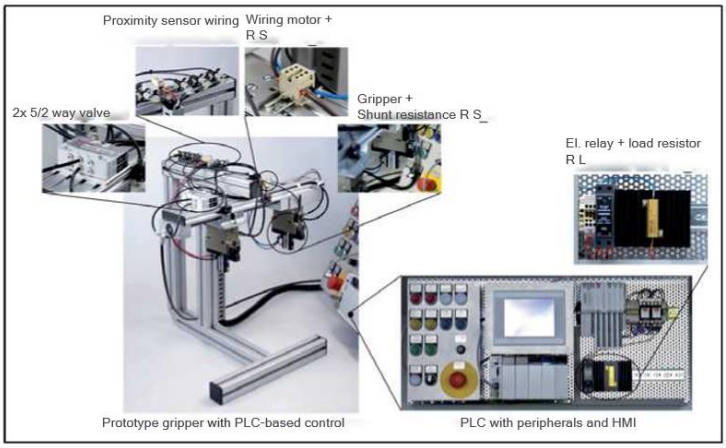


Figure A-22: Test diagram for technical states of modules and cells

A.4.5 Technical development of a semi-automated test procedure

The evaluation methodology developed in AS A.4.4 was implemented in a partially automated test procedure in collaboration with PB B. Cells whose voltage is within the nominal cell voltage range are tested for functionality using a discharge pulse. The following figure shows the prototype developed in PB B with the circuit for internal resistance measurement.



System level:

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Furthermore, an adapter developed in the LithoRec project enables the battery to be diagnosed even when it has been removed. To this end, both the hardware and the software were newly developed, implemented as prototypes and tested on various vehicle concepts from different manufacturers.

A.4.6 Process development for the end loading tool

The opening and dismantling of the cells processed in PB B requires prior discharging to ensure that no sparks are produced between the anode and cathode during the processing step. For this purpose, AS A.4.6 develops a method for a discharge tool for discharging cells.

Battery dismantling:

The battery system is discharged through an inverter so that the discharged energy can be used to supply the 230 V AC grid or through a constant current sink. Both devices can be used equivalently in the process. The decision depends solely on the expected (economic) advantageousness of using the residual energy quantity.

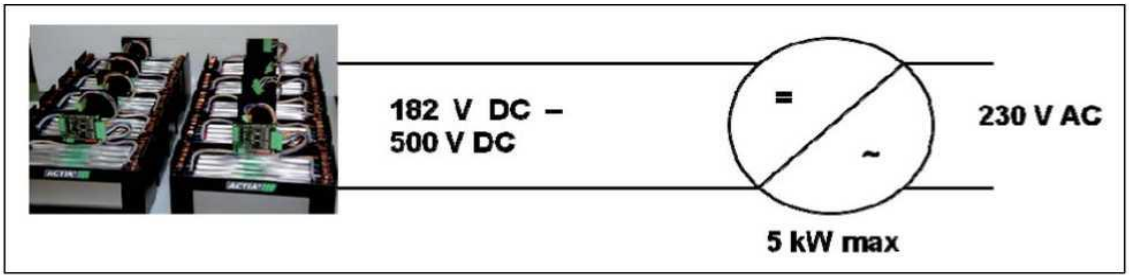


Figure A-23: Schematic diagram of the discharging process for battery systems

The properties of the components used are based on the assumptions made in the project regarding the expected battery systems. The BMS monitors the battery. Table A-19 shows the assumptions valid for the battery system parameters within the scope of the project.

Table A-19: Battery characteristics

System	Unit of measurement	HEV	PHEV	BEV
Number of cells		70	170	250
Energy content system	kWh	1	9	22
Number of parallel strands		1	2	2
Voltage min.	V	182	221	325
Voltage max.	V	280	340	500

The input voltage range of the discharger used must cover a range of 182 V DC - 500 V DC. Only a low discharge rate of 1C is permitted. The preliminary tests have shown that a higher discharge rate in this discharge step only minimally reduces the discharge time. However, a higher discharge rate would increase the cost of the discharger. The maximum output is therefore 5 kW. The cell voltage after discharge at system level is 2.6 of At this level, the battery can be handed over for dismantling and broken down into individual modules. Long-term storage of the battery modules should be avoided.

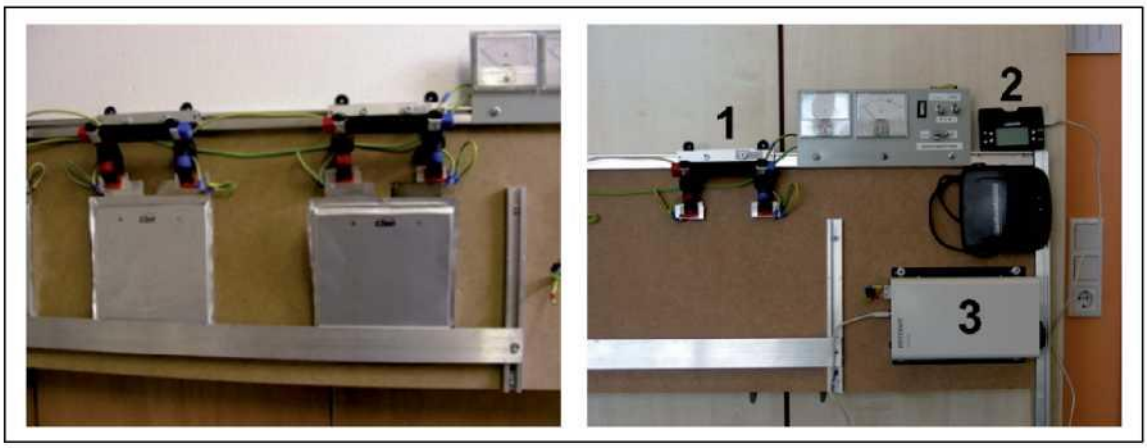
This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

A particular obstacle to discharging at system level is the protective function of the BMS. Normally, a battery system is not functional when removed, the protective relays are open. Discharging at system level can now only take place if functionality can be established through communication with the BMS. However, such an activation option is evaluated differently by the manufacturers for safety and warranty reasons. Alternatively, since the battery is being dismantled anyway, the protective function of the BMS can be bypassed and the discharger can be contacted by the recycling company, bypassing the relays.

Cell decomposition:

To ensure safety when dismantling the cells, the cells must be discharged to 0 V cell voltage. A simple resistive discharge process is used with the partners for this purpose. As part of the automation of the process chain, the cell can be unloaded using the gripper developed in PB B. The cell voltage at handover to the cell decomposition is 2.6 V, as the cells were discharged to this voltage at system level.

Figure A-24: Current cell discharge and gripper solution



A.4.7 Technical development of a semi-automated end loading tool

Cell decomposition:

Figure A-24 shows the implementation of the discharge at cell level with FRZ

Modified clamps (1) are used in order to be able to couple the cells to the discharging device even with different contact geometries. A 120 W resistor equipped with air cooling discharges the cells (2). Furthermore, an inverter can be connected and the battery discharged with a load of up to 300 W (3). The discharging process is monitored by a current and voltage meter. If the series connection of the cells reaches a voltage of 9V, the inverter is automatically switched off.

In addition to this process, a discharge tool was developed to make the continuous discharge of individual cells through an inverter semi-automatic. To ensure that the inverter operates as continuously as possible, a circuit is set up that allows Li-ion cells to be discharged and discharged cells to be replaced without interrupting the function of the inverter. This has a modular structure and consists of the following components:

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

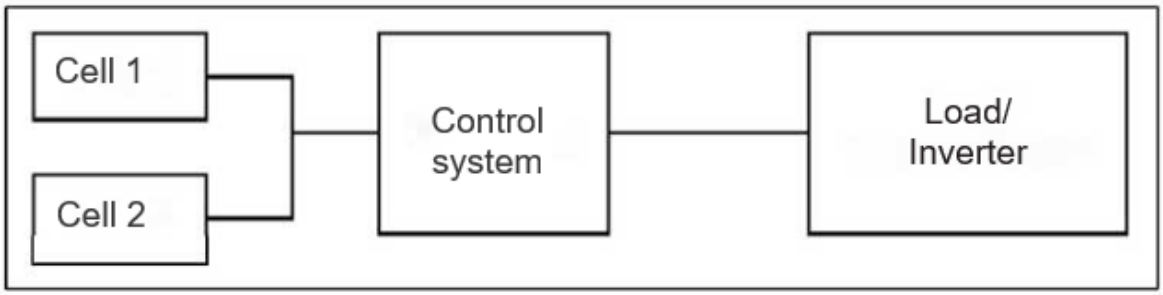


Figure A-25: Discharging tool circuit diagram principle

A.4.8 Testing the prototype

The unloading process and the developed unloading tool were tested at FRZ. Figure A-26 shows the course of a cell voltage during discharge through the inverter.

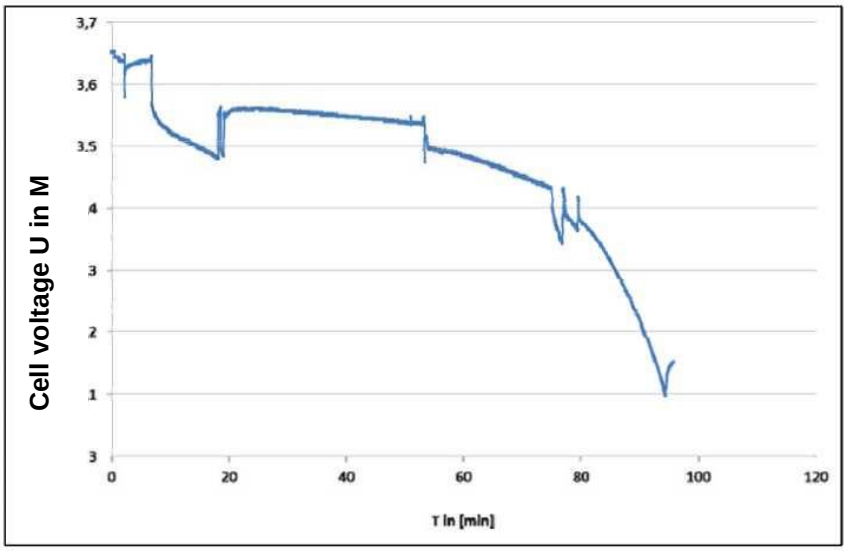


Figure A-26: Cell voltage curve during discharge

When a cell voltage of 3.1 V was reached, the total voltage at the inverter dropped below 9 V, so that discharging was interrupted and then continued at the resistor. The diagram also shows areas with different discharge loads. These occurred because different devices were operated on the inverter.

Furthermore, the effect of very different states of charge of the cells to be discharged was tested during the trial. Three cells with a voltage of 3.3 V and one cell with a voltage of < 2 V were connected to the discharging device. In this way, it should be checked whether the classification based on the voltage level before discharge is useful and necessary.

B Development of dismantling and recycling processes

The aim of **PB B** is to develop and test methods and processes for the recovery of battery system components. After the work packages mentioned above, the battery system is successively dismantled in order to develop the value components at cell level in addition to

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

polymer and metal fractions and battery electronics (BMS). These are electrolyte salts and in particular the metal-containing active materials. For the various processing strategies, hydrometallurgical processes are used to recover lithium raw materials for the synthesis of new, recycled active materials.

This is achieved by dividing the project into the following work packages:

- **AP B.1**: Mechanical dismantling into individual components
- **AP B.2**: Treatment and utilization of electrolytes
- **AP B.3**: Mechanical, thermal and chemical processing of the individual components
- **AP B.4**: Hydrometallurgical processing and recycling of non-ferrous metals

B.1 Mechanical dismantling into individual components

B.1.1 Product analysis and structuring of dismantling

Vehicle batteries form complex systems of varying size, weight and structure. Their design is primarily geared towards installation and space in the vehicle. Furthermore, each battery contains a large number of cells, which are usually flat (pouch cells) or round cells. The arrangement of the cells in modules and the circuitry within the batteries also influence the dimensions. Battery weights can vary from 10 kg to several hundred kilograms per system.

The aim of dismantling is to produce fractions that can be further processed in downstream processes.

The first step is to identify the battery and the condition of the cells using the enclosed or attached information. As things stand today, no standardized batteries are to be expected in recycling. The design, cell type, cell arrangement, cooling system and connection structures differ significantly.

Dismantling is therefore performed manually with the aid of standard manual or mechanical tools. Plug-in, adhesive, rivet and screw connections must be loosened to separate the individual components. At the same time, it must be ensured that the electrical charges present do not lead to short circuits or damage to components or persons.

Qualified electricians or persons with electrical training must be used for dismantling work on batteries. As a general rule, only qualified electricians may work on electrical systems and equipment. However, as qualified electricians are not always available in many companies, the employer can use electrically trained persons for certain tasks.

The electrician proves their qualification, for example, by training as a journeyman or skilled electrician. An electrically trained person is a person who has been trained by a qualified electrician for a specific job, informed about the assigned tasks and the dangers and instructed about the necessary protective equipment and protective measures.

The aim of **AS B.1.1** is to perform a product analysis and structure the dismantling of lithium-ion battery systems. IWF-TUBS performed an initial product analysis of a battery system provided in the form of a test dismantling. Figure B-1 shows excerpts from the photo documentation of the test dismantling.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

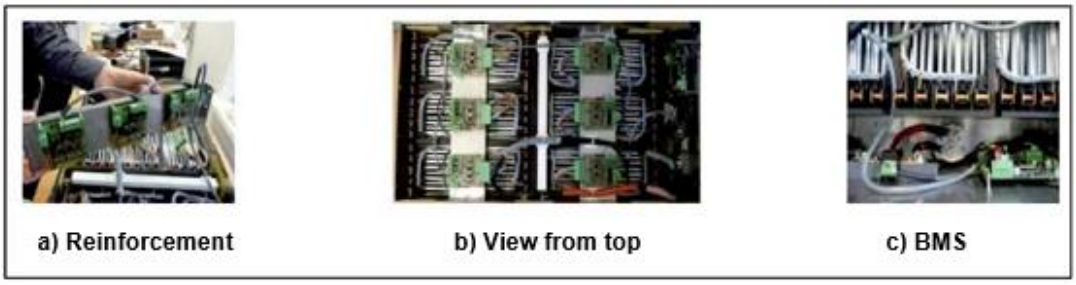


Figure B-1: Impressions of the test dismantling of battery system A

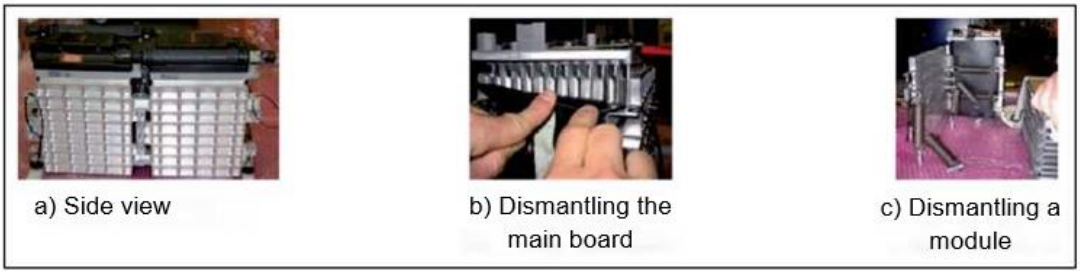


Figure B-2: Impressions of the test dismantling of battery system B

As part of the test dismantling, key dismantling data of the battery system was recorded. The following information was documented:

- Dismantling times for assemblies/components,
- Dismantled assemblies/components, as well as their material, weight, size, shape and accessibility,
- Tools used for the dismantling of an assembly/component,
- Type of connection between components/assemblies,
- Priority relationships,
- Evaluation of the automation capability of the individual dismantling processes,
- Safety aspects to be observed during the individual dismantling processes.

Table B-1 provides an example overview of the key dismantling data for the process step “Opening the battery system by removing the cover”.

Table B-1: Documentation of dismantling processes (example)

No.	Name of the process step	Predecessor	Quantity	Time (min.)	Dismantled part	Tool	Procedure
1	Opening the battery system by removing the cover	-	1	2:13:53	Cover	Cordless screwdriver	Screws
Connection	**Dismantling type**	**Safety aspects**		**Automatability**	**Element type**	**Material**	**Weight (g)**
Screws (20 x M3 10mm)	Non-destructive	Check contacting of the housing		Partial	Component	Stainless steel	1216
Size (mm)	**Shape**	**Accessibility**	**Base part**	**Comments**			
753	Flat block	Good	Housing	Very time-consuming dismantling step, poor quality screws, table should be accessible on both sides or rotatable			

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Removing the cover took approx. 2 minutes and 14 seconds. This is the dismantling time measured in the test dismantling, which does not correspond to the actual effort of an industrial dismantling process. This is influenced, among other things, by stochastic fluctuations, general performance and learning effects of the personnel (cf. [OHLENDORF 2006]).

Due to the large number of screws (number n = 20), the laborious dismantling of the cover was performed using a cordless screwdriver. A predecessor process step did not exist. The battery system was difficult to handle due to its heavy weight, so it is suggested that a table that can be accessed from both sides or a rotating storage system for the battery system be provided for the dismantling system planning. It is also suggested that the contacting of the housing should always be checked before this dismantling process step in order to rule out any risk of electric shock to employees. The automation capability of the process step was initially only roughly assessed as “partially” automatable.

Similarly, the dismantling process steps for the battery system under consideration were performed and documented up to the dismantling of individual cells. This data serves as the basis for further evaluations, e.g. the determination of optimum dismantling sequences. They also form the basis for the design and prototype implementation of the tool for integrated product assessment with regard to ease of dismantling, recycling efficiency and environmental impact in the disposal of battery systems in **PB F**.

Creation of connection graphs

Sub-step 1 of the methodology for the systematic analysis and evaluation of battery systems comprises the creation of connection graphs for the analyzed battery systems. Figure B-3 shows the connection graph for battery system A.

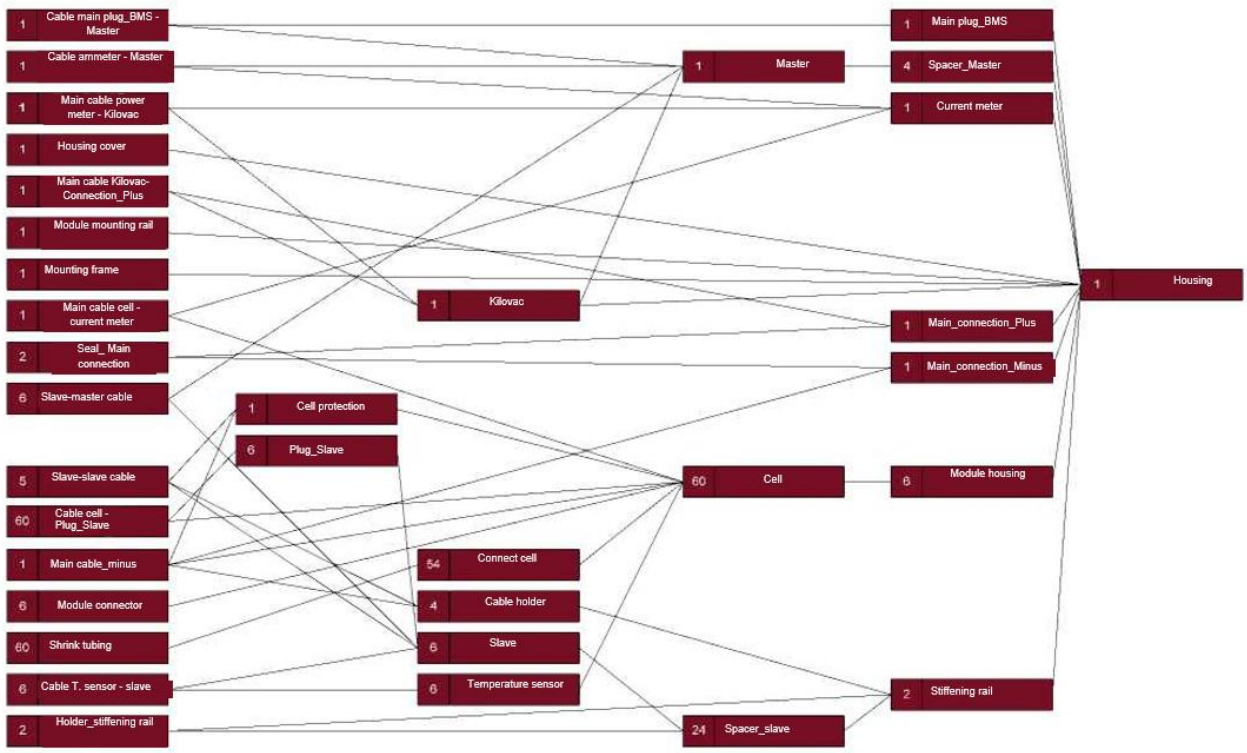


Figure B-3: Connection graph

The connection graph shows the connections between different component types in battery

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

system A. The connection graph does not allow any conclusions to be drawn about the type and number of connections. However, initial findings on possible complexity drivers for dismantling (e.g. high number of different component types, large number of connections between component types) can already be determined. Furthermore, the connection graph allows initial conclusions to be drawn about the design and structure of a battery system. In Figure B-3, the complex product structure can be recognized by the many connecting lines between the respective components. Analogous to the battery system A shown here, a second connection graph was created for battery system B. The findings are incorporated into **AS B.1.6** to derive requirements for battery design suitable for dismantling and automation.

Dismantling priority graphs and determination of dismantling parameters

The second step in the methodology is the creation of dismantling priority graphs. The data collected so far has been integrated into the tool for analyzing battery systems developed in **AS F.1**. Based on the data, dismantling sequences and times for valuable components (e.g. lithium cell, BMS, etc.) of the battery systems were determined and transferred to the respective dismantling priority graphs. The dismantling priority graph for a system A battery module is shown in Figure B-4.

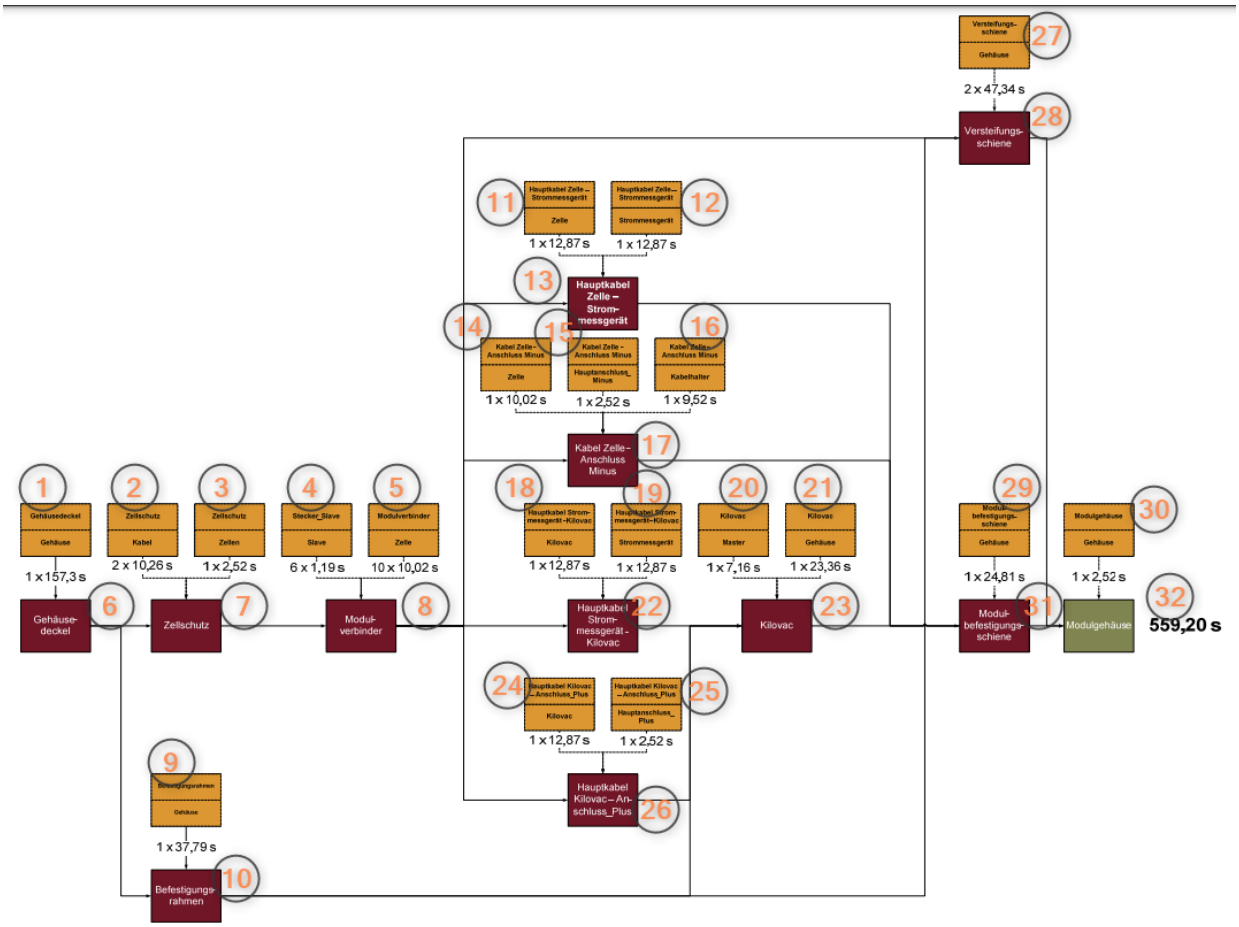


Figure B-4: Dismantling priority graph

Graph key:

1	Housing cover Cover	17	Cable cell – negative conection
2	Cell protection Cable	18	Main cable current meter-Kilovac Kilovac
3	Cell protection	19	Main cable current meter-Kilovac

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

	Cells		Electricity meter
4	Plug_Slave Slave	20	Kilovac Master
5	Module connector Cells	21	Kilovac Housing
6	Housing cover	22	Main cable current meter - Kilovac
7	Cell protection	23	Kilovac
8	Module connector	24	Main cable Kilovac - Connection_Plus Kilovac
9	Mounting frame Cover	25	Main cable Kilovac - Connection_Plus Main connection_ Plus
10	Mounting frame	26	Main cable Kilovac - Connection_Plus
11	Main cable cell current meter cell	27	Stiffening rail Housing
12	Main cable cell current meter Electricity meter	28	stiffening rail
13	Main cable cell - current meter	29	Module fastening rail Housing
14	Cable cell – negative conection Cells	30	Module housing Housing
15	Cable cell – negative conection Main connection_minus	31	Module fastening rail
16	Cable cell – negative conection Cable holder	32	Module housing

The dismantling sequence is shown from left to right. In Figure B-4, the housing cover must be removed before the cell protection in order to be able to remove the module connectors. The boxes shown in yellow indicate the respective connections between component types, e.g. a screw connection. The upper object must be detached from the lower object. To remove the cell protection, the connections to the cable to the cells must therefore be disconnected. It takes 10.26 seconds to disconnect the double connection to the cable. The total dismantling time is 559.20 seconds.

The dismantling of the battery systems under consideration down to cell level is very time-consuming and therefore cost-intensive at approx. 57 and 101 minutes. In battery system A, this can be explained by a large number of constructive priority relationships. Battery system B, on the other hand, has a simple modular design. Due to the technology used for cell contacting (in this case a welded connection), the dismantling of all cells is more complex than the dismantling of all cells in battery system A without appropriately designed special tools and the associated expert knowledge.

B.1.2. Concepts for semi-automated dismantling steps

The modules and battery systems handed over to TU-BS by IME ACTIA were dismantled by IWF-TUBS at the start of the project. Dismantling times, dismantling steps and priority relationships were recorded and evaluated using a software solution from IWF-TUBS. Through this work, IK-TUBS was able to develop and present initial design and improvement proposals. Battery systems from AUDI and VW were also made available to the TU-BS for dismantling. The AUDI and VW battery systems were dismantled, documented and evaluated for recyclability by the TU BS in the same way as the IME ACTIA battery system. The results are available to the TU-BS.

The dismantling was performed by TU-BS employees, documented and structured and evaluated in IWF-TUBS software. The automation options for the dismantling steps were assessed and evaluated.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

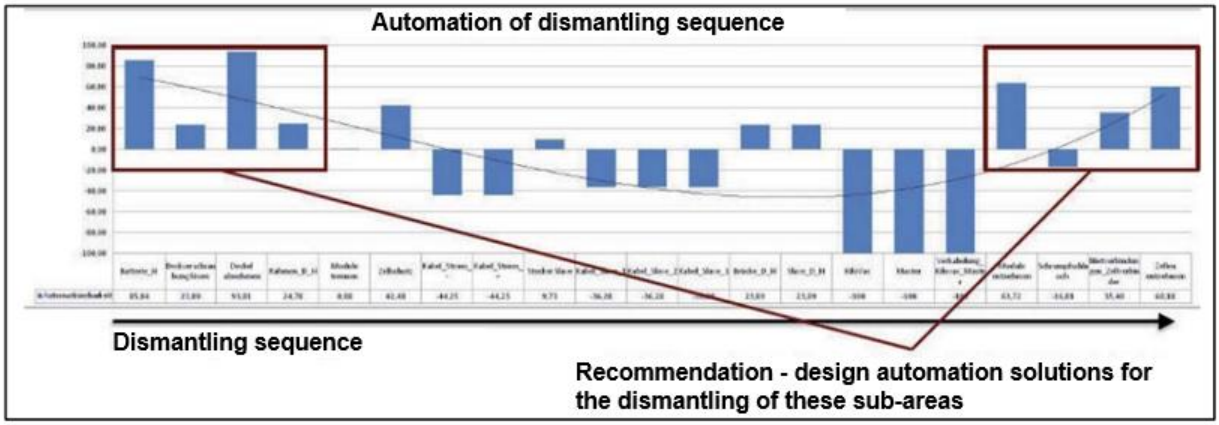


Figure B-5: Example assessment of automation capability

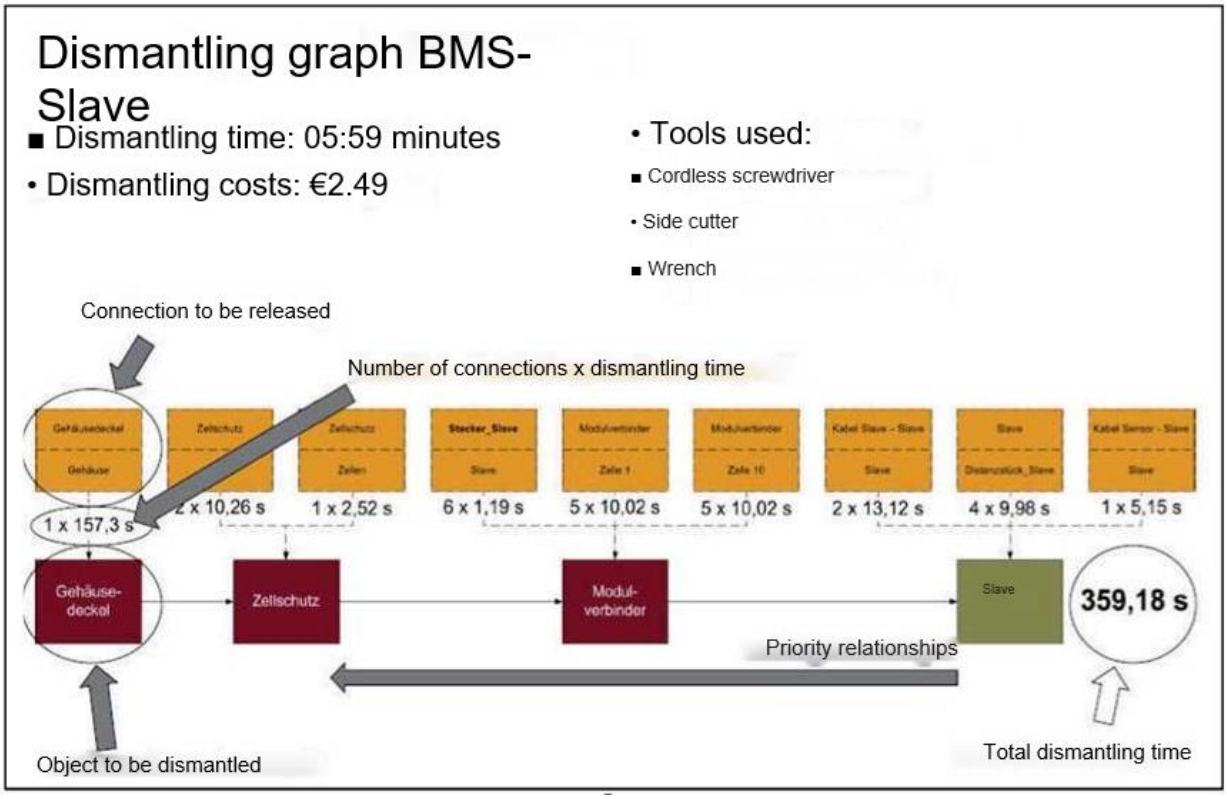


Figure B-6: Example evaluation of dismantling

A profitability analysis for dismantling work was performed by IWF-TUBS. The results depend on the complexity of the battery systems and can be realized efficiently and semi-automatically, at least for module dismantling. From today's perspective, it will be more efficient to open the battery system and dismantle the modules manually.

Based on the manual dismantling of the battery systems performed in **AS B.1.1** and the characteristic values generated, e.g. dismantling assembly time, connection to be released, etc., a system was developed and applied to assess the automation capability. Both the individual steps and the entire dismantling sequence were evaluated. The evaluation system is based on a catalog of criteria comprising 20 weighted criteria. The following overarching categories were taken into account:

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- Process-related criteria (e.g. complexity of a dismantling movement)
- Safety-related criteria (e.g. distance to a potential)
- Part-related criteria (e.g. part weight in kg)
- Economic criteria (e.g. urgency of automation)

The criteria are assigned to the key figures

- (Technical) automation of a dismantling step (TAD)
- Necessity of automation (NA)

Figure B-7 shows the English version of the criteria catalog for process-related, safety-relevant and economic criteria for the evaluation of the dismantling step “Handling of the battery system from the delivery location to the dismantling site”. The criteria relevant for the evaluation were rated on a scale of -1, 0, 1 (negative, neutral, positive fulfillment of criteria with regard to automation) and combined into an overall rating by multiplying them by the weighting factor. The weighting factors were determined using the pairwise comparison method. The sum of all valuation results is expressed by the key figures TAD and NA in accordance with the allocation.

	Description of the disassembly operation	Handling the battery system from the delivery to the disassembly area	Points	Weight	Total
Process-related criteria	Number of disassembly motions	1	-1	4	-4
	Complexity of disassembly motion(s)	0,9611	1	16	16
	Accessability of the join patch/the part to disassembly	Join patch without any restrictions accessible	1	12	12
	Automation potential of the disassembly tool	9	1	11	11
	Joining technique	screwed	0	8	0
	Accuracy of the positioning of the disassembly tool [+/- mm]	10	1	4	4
	Suspectance to failure	low	1	13	13
	Duration of manual disassembly	10	0	15	0
Safety-related criteria	Direct involvement of hazardous material	no			
	Disconnection of current carrying cables	no			
	Distnace to an electrical potential	save			
	Legal auxiliary material for manual disassembly	none	-1	30	-30
Part-related criteria	Geometrical workpiece dimension (bounding geometry) [mm x mm x mm]	600 x 500 x 300			
	Weight [kg]	> 10 kg	1	19	19
	General characterization	Blockpart	1	5	5
	Specific form elements (defined purchase für disassembly tool)	Face (e.g. vacuum gripper)	1	8	8
	Number of specific form elements (defined purchase für disassembly tool)	1	0	6	0
	Properties during force influence	inherently stable	1	15	15
	Part behaviour after disassembly	stackable	1	2	2
Econ. criteria	Economical priority of automation	Realisation with highest priority	1	7	7
	Equipment costs (rough estimation)	< 5.000€	1	26	26
	TAA	86			
	NA	19			

Figure B-7: Criteria catalog (English)

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The dismantling steps determined were evaluated using this system and the key figures TAD and NA were determined both for the individual step and for the entire dismantling sequence. A portfolio representation was used to evaluate the individual steps (see Figure B-8). The key figure TAD was plotted on the ordinate, NA on the abscissa. The evaluation of the corresponding quadrants I-IV leads to the areas 1 and 2 relevant for the project:

1. Focus "*LithoRec*": The dismantling sequences are fed into a system design.
2. Medium/high research needs can be identified: not feasible within the project duration

The dismantling steps determined were evaluated using this system and the key figures TAD and NA were determined both for the individual step and for the entire dismantling sequence. A portfolio representation was used to evaluate the individual steps (see Figure B-8). The key figure TAD was plotted on the ordinate, NA on the abscissa. The evaluation of the corresponding quadrants I-IV leads to the areas 1 and 2 relevant for the project:

3. Focus "*LithoRec*": The dismantling sequences are fed into a system design.
4. Medium/high research needs can be identified: not feasible within the project duration

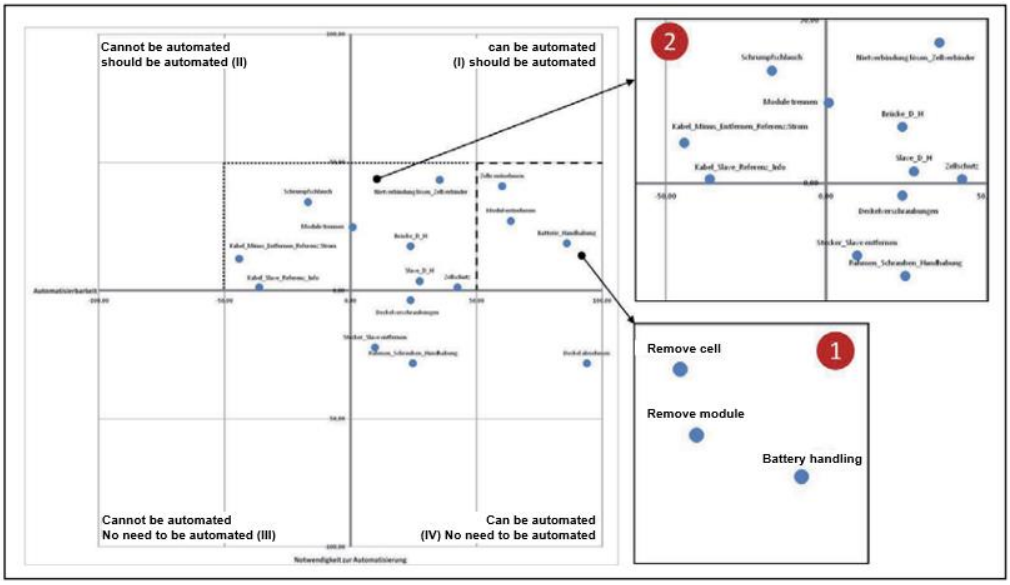


Figure B-8: Portfolio representation for assessing the automation capability for the individual step

In the process-oriented representation, the characteristic values for TAD and NA were shown according to the dismantling sequence. In areas with several "easily" automatable, consecutive individual steps, a potential for integrating these dismantling sequences into a (partially) automated system can be identified. The investigations led to the conclusion that the dismantling steps

- Handling a battery from the delivery point to the dismantling site
- Remove module from a battery system
- Remove cell from a module

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

could be used for further conceptualization. VDI Guideline 2221 “Methodology for developing and designing technical systems and products” [VDI 2221] is used to develop concepts for (partially) automated dismantling in order to systematically increase the degree of concretization of the selected dismantling steps.

For the step “Handling a battery system from the delivery location to the dismantling site”, three automation concepts with different degrees of automation and worker deployment were presented. The results are summarized in the following Table B-2:

Table B-2: Compilation of concepts for handling a battery system from the delivery point to the dismantling site

Degree of automation	Worker deployment [persons/shift]	Handling device	Gripper	Comments
100%	0.05 (maintenance etc.)	Industrial robot KUKA KR 1003 comp	2 x Schmalz FXC vacuum area grippers	planar gripping surface required
50%	1	Articulated boom Dalmec Posifil column-mounted device PFC	2 x Schmalz FXC vacuum area grippers	Load capacity up to 120 kg,
0%	2	Hourly rate per worker of 30 €/h and 15 sec. per handling process at 80% capacity utilization		

For the initial assessment of the number of units per time unit from which a more highly/fully automated solution is preferable, an economic comparison of the concepts was performed using the machine hour rate and cost comparison calculation. The disadvantage of this static method is that only future developments cannot be considered and that investment decisions are not based exclusively on costs. Nevertheless, this method can be used for an initial estimate, as the numerous unknown factors in dismantling system design do not allow a more precise analysis.

After the manual dismantling of three different battery systems, it became apparent that the shape variance of the individual battery modules is so great that, despite a positive evaluation of this dismantling step, conceptual design is not sensible, so that the rough planning for an automation system for handling a battery cell must be prioritized. This is done with special consideration of **AS B.1.4** and **AS B.1.5**.

The concept phase for designing an element for dismantling is described within this AS, the mechanical design, control architecture and operating software in **AS B.1.4**. According to the evaluation system described, the “Remove cell from module” step was rated positively, which is significantly influenced by a high level of safety relevance, as some charged battery cells have to be handled and this is directly followed by the feeding of the cell opening. This should have a high degree of automation due to the direct involvement of materials that are harmful to health. This demo step is qualified in the following to the effect that a system for handling battery cells is being developed, as it has been shown during manual dismantling that the battery cells cannot be separated non-destructively or are arranged so close together that a gripper cannot be adequately positioned to ensure a secure grip. To achieve this, the concept

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

of flexibility and status detection were integrated into the development. Based on this selected task “Development of a gripper for handling pouch battery cells of different formats with integrated voltage measurement and internal resistance determination”, a list of requirements was drawn up, subtasks of the system defined and a solution space created using a morphological box. From this, possible system solutions were selected and compared. At the same time, a commercially available gripper was researched and evaluated as a subsystem. An excerpt from the list of requirements is shown in Table B-3:

Table B-3: Extract from the list of requirements for the gripping device

Structure	No.	Designation	Values, data	Anf. Type
Functional requirements	1.1	Enable accessibility of different battery sizes		F
	1.2	Enable positioning of the gripper	automatically	F
	1.3.	Enable measurability of battery voltage/internal resistance	displayable	F
	1.4	Travel speed of the guide	> 25 mm/s	M
	1.5	Electrical voltage of the motor	U=24V DC	F
	1.6.	Total weight gripper	< 5kg	M
Avoid disruptive effects	2.1	Avoid movement during operation		F
	2.2	Voltage measurement deviation	< 0.1 V	M
Spatial requirements	3.1	Simplify assembly of the gripper system (modularity)		W
	3.2.	Simple routing of the cabling		W
Economic requirements	4.1	Maximize the number of standard and purchased parts		F
Regulatory requirements	5.1	Aim for a modular principle		W

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The result of this gripper conceptualization and dimensioning is published in [Schmitt, 2011]. The functionalities of the gripper are summarized here. The main requirement is the secure gripping of different sized pouch cells. For this purpose, two parallel jaw grippers were selected, the distance between which can be changed by means of a spindle linear axis. The axle is driven by a DC motor with planetary gearbox. The position of the grippers is determined by inductive proximity sensors. However, this only allows a low positioning accuracy, which is sufficient for the requirements in dismantling. Any geometric changes in the battery cells can be achieved by simply moving the proximity sensors. Separating reprogramming of the PLC is not necessary. The contacts of the battery cells were selected as gripping surfaces in order to realize an in-process determination of the cell's condition. The current voltage value should be measured and the internal resistance determined as characteristic values, as this data can be evaluated quickly and with the desired control technology. Separating, cost-intensive measurement technology should be avoided. Furthermore, a (modular) PLC-based control system for the gripper system was chosen in order to use industrial, partially standardized standard components as far as possible. The principle of the gripper system and the control architecture are shown in Figure B-9. A more detailed description of the relevant subsystems and functionalities is provided in AS B.1.4.

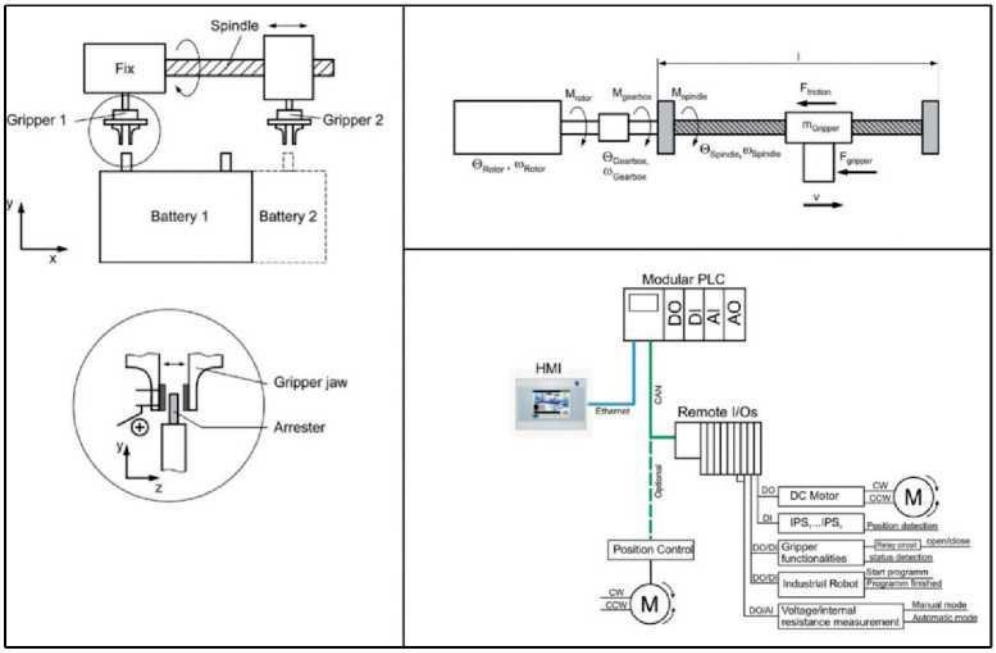


Figure B-9: Principle of the gripping device (left); parameters for motor design (top right) and control architecture (bottom right)

B.1.3 Design of alternative dismantling systems (layout, linking of workstations/workplaces)

In several joint working meetings (EC, IWF-TUBS, I+ME), dismantling options, primarily for batteries and modules, were discussed (with the exception of cell dismantling - input is still expected from the project partners involved) and evaluated with regard to suitable workplace design and process technology. In order to describe the correct conceptual design, IWF-TUBS has recorded physical technical functions, economic and safety-relevant requirements and related them to the carrier system, drive system, transport system and active system. The

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

summary and schematic illustration of a possible dismantling process is presented and described by IWF-TUBS.

Alternative dismantling systems are characterized by the interlinking of work steps and an increasing degree of automation. It is important to link the steps that are required even for small quantities of used batteries.

Initially, a high degree of manual work determines the dismantling process. Handling equipment such as hydraulic lifting devices and transport systems with roller conveyors must be provided to support the processes. Lifting devices are particularly necessary for the initial feed to the battery identification, sorting and subsequent discharging station. Due to the dangerous goods regulations, the batteries are packed in special, suitable and approved containers for transportation. It can be assumed that the batteries from these containers are fed directly into the dismantling system. As a rule, the batteries lack mounting options such as eyelets for attaching lifting gear. Due to the high battery weight, systems with grippers or suction lifters must be provided to lift the batteries out of the containers onto a transport system, e.g. roller conveyor.

For large batteries that can have dimensions of up to 2 m in length and 1.5 m in width, island stations are more advantageous for dismantling. A dismantling section usually only allows access from two sides. Large systems require accessibility from all sides

In addition to linking the dismantling steps, it makes sense to automate dismantling processes such as battery opening, cell removal and cell opening with filling material removal (stack/wrap). However, a high degree of standardized battery systems is required here. Experience from the recycling of old electrical appliances such as telephones, computers and monitors shows that automated systems quickly reach their limits.

Only the slightest changes to components, such as the arrangement and type of connections and screws, are detrimental to the automation of dismantling.

The aim of this step is to select the individual stations of the dismantling system and to define and roughly dimension the required elements. In addition to the workstations, the transport equipment used to link the individual stations was also considered. All elements were then brought together to form a complete dismantling system and combined in an overall layout. The design of the various alternatives of the dismantling system is based on technical and economic aspects.

The delivered battery systems are temporarily stored and then discharged in a first step. Discharge is described in **AS A.4.6** to **AS A.4.8**. In the next intermediate step, the battery system is roughly pre-sorted according to various criteria such as type and condition. Pre-sorting according to manufacturer type makes the number of variants more manageable and allows larger batches of a battery type to be processed. A conveyor transports the Li-ion battery systems to a cleaning cabin and then to the dismantling stations or locations. There, the battery system connections are separated using the appropriate tools and the individual assemblies and parts as well as the shapeless materials are separated. Depending on the battery type, the dismantling process can be performed either destructively or non-destructively. The dismantled assemblies and parts can then be transported away as fractions, cleaned and possibly reused or recycled. Components that cannot be recycled or used are disposed of. The exposed cells of the lithium-ion battery systems are fed into the cell opening process. Cell opening then takes place according to the techniques developed in **AP B.2**,

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

whereby secondary raw materials can be obtained. The general procedure for dismantling battery systems is shown schematically in Figure B-10.

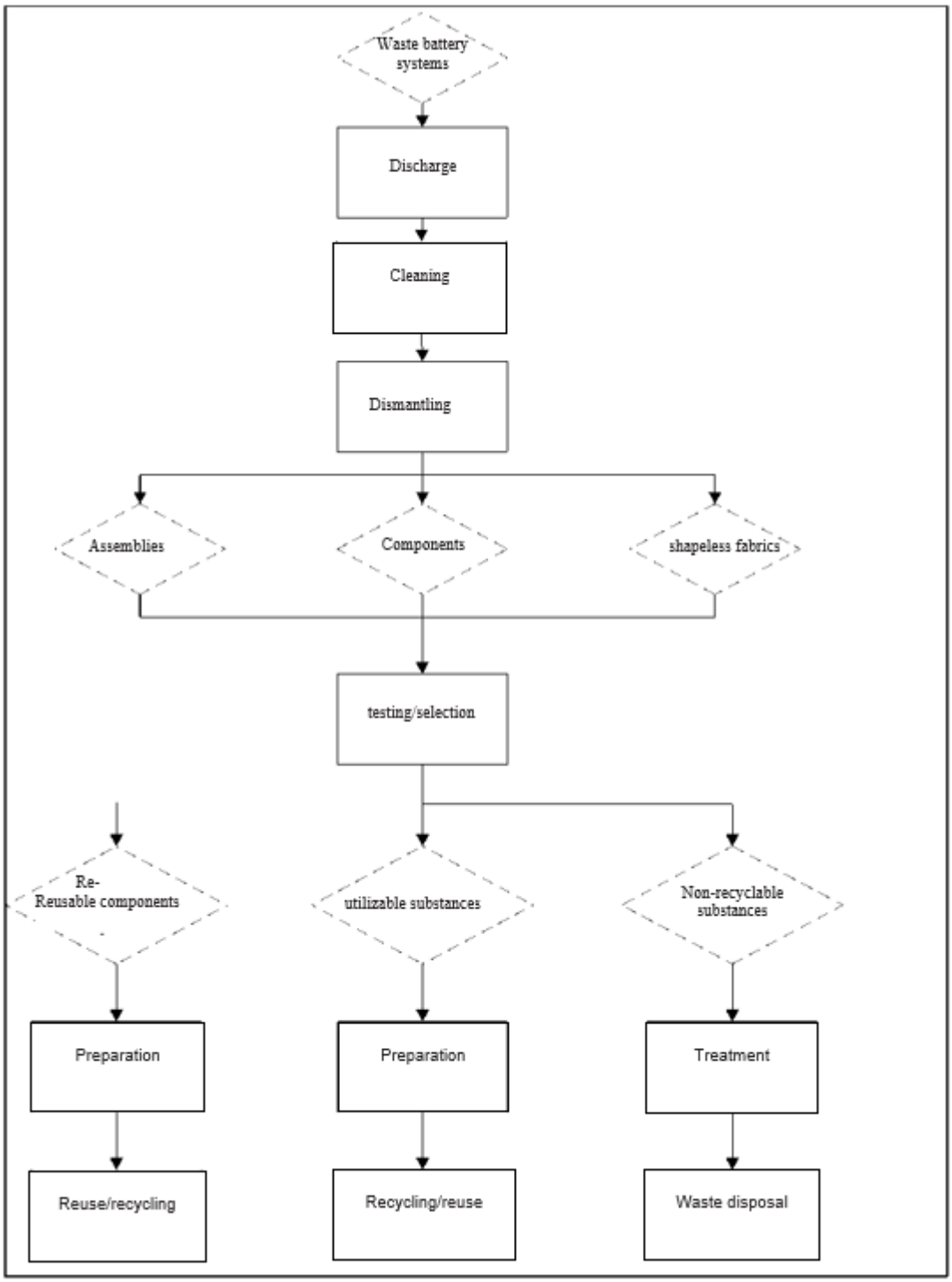


Figure B-10: Schematic of the general dismantling of battery systems14

Recycling alternatives for lithium-ion batteries

Based on the scenarios defined in **PB A**, each of which involves a different volume of battery systems, two different recycling alternatives are developed and designed accordingly in order to meet the increasing requirements over the course of battery collection and recycling. The

[14] based on IREAK (1999), p. 36.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

basis for this is the “realistic” scenario from **PB A** from 2015 and 2030. Due to the significantly higher volume of used batteries in 2030, the “political” scenario is also discussed and the additional measures that would have to be taken for the increased volume of used batteries.

Cross-scenario statements

PB A is used to determine the average battery system weights in addition to the mass-related volume of used batteries. The combination of these two data sets can be used to calculate the quantity-related volume of used batteries (quantities) (see Table B-4). Here again, only the two “realistic” scenarios “2015 realistic” and “2030 realistic” are considered in more detail.

Table B-4: Return quantities of battery systems (number of units) for the “2015 realistic” and “2030 realistic” scenarios

Return quantities battery systems	“2015 realistic”	“2030 realistic”
Total [units/a]	526	114,311
HEV [units/a]	158	4,845
PHEV [units/a]	321	69,360
BEV [units/a]	47	40,106

Furthermore, it is assumed that the number of individual battery cells per battery system has an average value of 70 cells for hybrid electric vehicles, 170 cells for plug-in hybrid electric vehicles and 250 for battery electric vehicles. These values are the same for all scenarios.

Realistic 2015” scenario

For the “2015 realistic” scenario, the battery systems available in the project serve as the basis for the dismantling design. These battery systems do not allow non-destructive dismantling of the battery cells. Re-use and further use of the cells is therefore out of the question.

The number of different battery systems is set at ten. The standardization of cell types or minimization of the number of cell types used, which is crucial for automated cell dismantling, does not exist here. For this scenario, it is assumed that both pouch cells and round cells are used in the battery modules.

Based on the dismantling studies performed as part of the LithoRec project, an average dismantling time of 100 minutes is assumed for the “2015 realistic” scenario. This is a 100 percent manual dismantling. No automation steps are implemented in the dismantling process.

Assuming that in this “2015 realistic” scenario a total of 526 battery systems are returned throughout the year, with a high number of variants that cannot be dismantled non-destructively, it can be determined on the basis of the suitability of organizational characteristics that the most suitable form of dismantling organization is the single station.

This is an object-related organizational principle in which the battery system must be dismantled manually. Due to the high degree of variant flexibility, the material flow is also designed flexibly so that it can be adapted to the different dismantling times. Material is supplied centrally from a central warehouse, while material removal is organized decentrally from the individual workstations.

The battery systems are placed on a workunit carrier and transported from the warehouse to

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

the workstations using a forklift. No holding or clamping devices are used so that the worker can move the workunit freely.

Table B-5 shows the dismantling system for the “2015 realistic” scenario in the form of a morphological box.

Table B-5: Morphological box of the dismantling systems for the “2015 realistic” scenario

Product	*Product group*	LITB				
Organization	*Organizational principle*	Object	Execution			
	Arrangement structure	Single seat	Cell	Island	Net	Line
Dismantling process	*Degree of automation*	manual	hybrid	automated		
	Material flow	rigid	flexible			
	Presorting	with	without			
	Dismantling	destructive	non-destructive			
Material flow	*Material inflow*	central	decentralized			
	Material removal	central	decentralized			
	Storage/sorting	central	decentralized			
Operating resources	*Robot type*	Portal	Articulated arm	Scara	Coordinates	
	Gripper	Baking	Vacuum	Magnet	Pen	
	Workunit carrier	with	without			
	Holding and clamping devices	with	without			
	Conveyors	Roller conveyor	Carrier chain conveyor	Circle conveyor	Power and free conveyor	Forklift truck

Due to the small quantity of regressing batteries, it is sufficient to provide a general workplace that can be used for battery dismantling, but alternatively also for the dismantling of other

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

products. With 526 battery systems, based on 252 working days per year, 2.1 battery systems per day must be dismantled

The average dismantling time per battery system is 100 minutes. This means that the battery systems can be dismantled within 3.5 hours. A single dismantling station is therefore sufficient. The tools required include standard tools such as screwdrivers, hammers and wrenches, as well as pliers. Special tools are not provided.

Figure B-11 shows a possible layout for such a workstation.

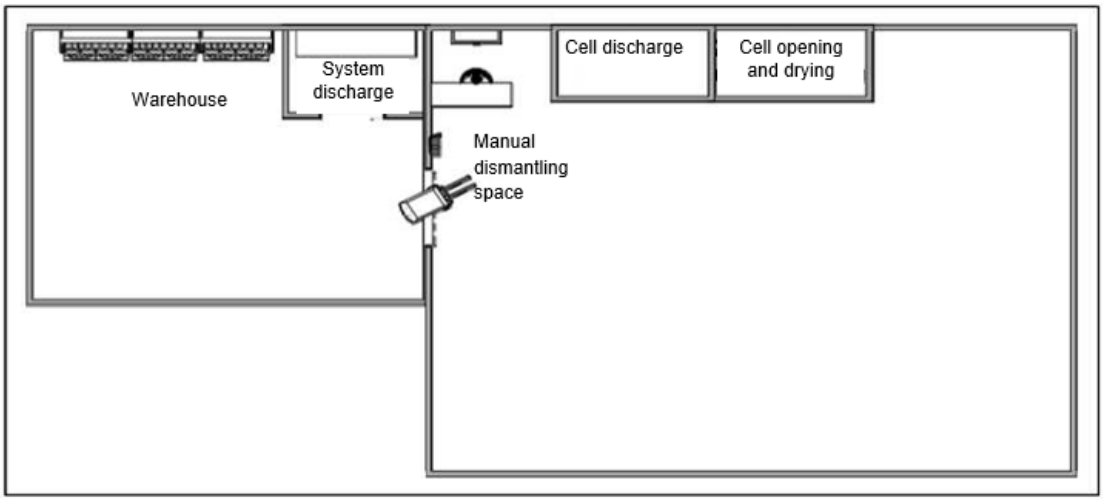


Figure B-11: Layout of a dismantling system for the "2015 realistic" scenario

In the "2015 realistic" scenario, it is also possible to link the workstations through roller conveyors. The battery systems would be loaded by forklift truck into the system unloading area and then conveyed by roller conveyors to the manual dismantling area and then on to the cell unloading and cell opening or cell drying area.

Scenario "2030 realistic"

As it must be assumed that the battery systems in 2030 will differ fundamentally from the systems available today due to the rapid technical development, a battery system developed on the basis of the proposals from **PB F** serves as the basis for the design of the dismantling system in 2030. Corresponding design changes to the battery systems are considered to have already been implemented and thus influence the design of the entire dismantling system. Part of the optimization proposals will be measures that enable non-destructive dismantling of the battery systems down to cell level. This is not possible with current battery systems. In the "2030" scenarios, it is assumed that pouch cells and round cells will be used.

Due to technical standardization on the part of politics and industry and based on economic synergy effects, it is assumed that the number of different battery systems will be reduced from the currently assumed ten systems to three different traction battery systems.

In contrast to the "2015 realistic" scenario, this scenario assumes a high degree of automation of around 70 percent. The total dismantling time is 30 minutes, as the battery system has been designed to be easy to dismantle and therefore allows a high degree of automation. Manual dismantling takes 10 minutes, while 20 minutes are estimated for automated dismantling.

In the "2030 realistic" scenario, the total return volume of the battery systems is 114.311 units. Since a degree of automation of 70% is assumed and the number of variants is low, as well as

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

the quantity of battery systems to be processed is high, the organizational principle of the dismantling line is chosen, which is structured according to the principle of direction. The individual automated stations of the dismantling line are geared towards performing a specific task. Dismantling is non-destructive.

The material flow is flexible and designed without pre-sorting. The incoming battery systems are provided with a barcode, which can be used to read the technical data of the battery through a scanner and load the corresponding programs required by the dismantling robots. Both material inflow and storage are organized centrally, while material removal is decentralized.

Table B-6: Morphological box of the dismantling systems for the "2030 realistic" scenario

Product	*Product group*	**LITB**				
Organization	*Organizational principle*	Object	**Execution**			
	Arrangement structure	Single seat	Cell	Island	Net	**Line**
Dismantling process	*Degree of automation*	manual	**hybrid**	automated		
	Material flow	rigid	**flexible**			
	Presorting	with	**without**			
	Dismantling	destructive	**non-destructive**			
Material flow	*Material inflow*	**central**	decentralized			
	Material removal	central	**decentralized**			
	Storage/sorting	**central**	decentralized			
Operating resources	*Robot type*	Portal	**Articulated arm**	Scara	**Coordinates**	
	Gripper	**Baking**	Vacuum	Magnet	Pen	
	Workunit carrier	**with**	without			
	Holding and clamping devices	**with**	without			
	Conveyors	**Roller conveyor**	Carrier chain conveyor	Circle conveyor	Power-and-Free conveyor	**Fork-lift truck**

Irrespective of the assumption that the battery systems are constructed according to the model of the proposals developed in AP F, it is necessary to provide individual workstations according to the model of the "2015 realistic" scenario in order to be able to recycle any old battery systems that may still be available and to be able to process damaged battery systems.

Figure B-12 provides an overview of what the layout of a dismantling system with automatic and manual stations could look like.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

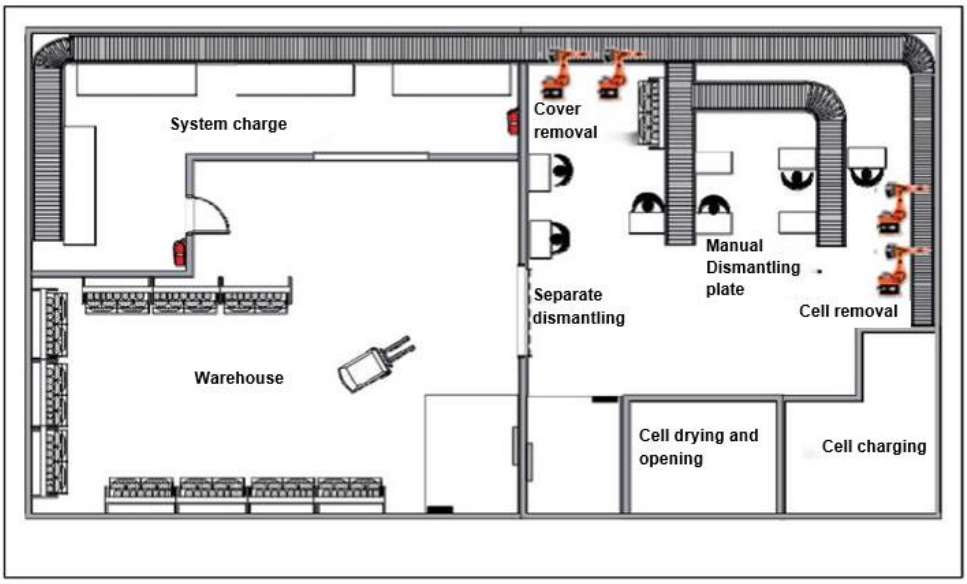


Figure B-12: Layout of a dismantling system for the "2030 realistic" scenario

The gripper developed and tested in steps AS B.1.4 and AS B.1.5 is used to remove the battery cells.

Scenario "2030 political"

The same background assumptions apply for the "2030 political" scenario as for the "2030 realistic" scenario. The only difference is the declining number of battery systems. Analogous to the results from PB A, this results in quantities that are on average around eight times as large as the returns from the "2030 realistic" scenario (see Table B-7).

Table B-7: Return quantities of battery systems (number of units) for the "2030 political" scenario

Return quantities battery systems	"2030 political"
Total [units/a]	924,819
HEV [units/a]	18,947
PHEV [units/a]	668,150
BEV [units/a]	237,722

The total quantity of regressing batteries amounts to around one million systems. This high volume must be taken into account when designing the dismantling system. In the "2030 political" scenario, the total return volume of the battery systems is 924.819 units. This is around eight times the amount of the "2030 realistic" scenario. Since, apart from the total volume, the conditions between the two 2030 scenarios are identical, two paths can be taken. Either the dismantling system of "2030 realistic" is scaled up and 40 workstations are set up or, alternatively, a second location is opened, which together with the first location operates 40 workstations in two shifts.

The technical design of the dismantling systems for the "2030 political" scenario is analogous to the design of the dismantling system for the "2030 realistic" scenario.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

In **AS B.1.3**, various dismantling systems were developed with the aid of a flow chart and morphological boxes, as well as the scenario technique, which were dimensioned depending on the return volume of the spent batteries. The transition between the two scenarios presented here will not be abrupt. It is not possible to link this transition to a specific number of batteries to be processed. Rather, as the number of used batteries increases, there will be a gradual changeover in dismantling, which will initially take the form of an increase in manual dismantling stations with interlinking of the dismantling stations by roller conveyors. If the prerequisites for automation are met (e.g. minimization of battery types or modularization of batteries into standardized modules and assemblies), the manual workstations are gradually automated as far as possible. Due to the uncertain data situation regarding future battery systems, it is not possible to make precise statements regarding the required quantities that will result in a gradual change in the dismantling system.

B.1.4 Design of the elements of the dismantling system

As part of *LithoRec*, J+ME has created a software function extension that has been integrated into the “MultiDiag” multi-brand diagnostic device. With this extension and the ACTIA workshop diagnostics PC, it was possible to map and log an initial system identification, a status analysis and a dynamic characteristic for load/charge operation for battery systems. This diagnostic technology for batteries was presented to the project partners. It is a technical basis for the evaluation of batteries. However, the functionality created is not yet sufficient to cover use as a complete battery diagnostic device for all battery technologies, or to be fully usable as a condition tester for the analysis, evaluation and prognosis of lithium batteries. Only the combination with load/charging technology and, if necessary, with roller dynamometers and the configuration of test procedures makes this test environment for evaluating batteries more complete. The main problem is in particular access to unknown battery and BMS systems and the variety of connector assignments as well as the type and scope of OBD and CAN configuration (protocols). Service technicians and recyclers also have different information interests. The service case requires, for example, the saving of error and warranty data, the diagnosis of defects and the assessment of repair and reusability. Recycling companies primarily want information on system voltage, number of cells, the type of electrochemistry, any risks and safety problems as well as dismantling information. Conclusion: The development and expansion of battery diagnostics technology will and must continue - particularly due to the growing variety of battery and system technology. An initial expandable basic functionality for battery diagnostics was realized as a prototype as part of *LithoRec*. Figure B-13 shows the MultiDiag multi-brand diagnostic device for vehicle technology, which was set up with basic battery analysis software for the external determination of the condition of large-format lithium batteries:

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure B-13: Multi-DIAG diagnostic device

Appropriate measurements, system procedures and forecast reports could be used to determine the further use of lithium batteries or the replacement of components. For batteries that cannot be reused or “non-repairable”, the only remaining option is to dismantle the system and dispose of them properly through a recognized battery recycling channel.

Test equipment for detecting residual battery charge:

Test equipment must be matched to the respective battery. Battery-specific devices with coordinated connection options are required. Various batteries from electric vehicles or hybrid vehicles reach the recycling plant. The batteries are from different manufacturers and are in different states of ageing. A universal device for testing residual charge does not exist and cannot be designed due to the variety of batteries. In addition, most batteries are disconnected from the outside by removing a “disconnector” and without opening the battery, neither voltage nor current can be measured even with a commercially available measuring device.

It is therefore usually not possible to make a statement about the state of charge or measure the capacity of the batteries. Only a rough indication of the battery status - charged or faulty - can be drawn from the voltage to be measured.

Safe discharging of the battery is only possible if the cells are connected separately to a discharger and discharged individually. However, as this requires the battery to be completely dismantled and the cells to be present individually, it is currently practically impossible to dismantle a completely discharged battery, which is desirable for safety reasons.

As long as the cells or cell blocks are not electrically isolated from each other, the stored residual energy poses an electrical hazard to the dismantling personnel.

For this reason, appropriate work protection and protective clothing must be worn.

- Wear electrically insulating and arc-resistant protective clothing (jacket, trousers) for live working in accordance with VDE
- Wear electrically insulating gloves and shoes in accordance with VDE
- Use of isolated tools
- Insulation of loosened connections until the connections are finally dismantled.

The following tools and aids are required for dismantling:

- Pneumatically or electrically driven screwdriver
- Side cutters (insulated if possible)
- Cable shears (preferably insulated)
- Bolt cutters
- Torx bit Tx 15, 20, 25,
- Screwdriver Tx 15 (preferably insulated)
- Phillips screwdriver (preferably insulated)
- Allen bit 4mm, 5mm, 6mm

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- Socket wrench and open-end wrench M6, M8, (insulated if possible)
- Mounting lever
- Voltage tester with measuring properties
- Insulating tape/wide adhesive tape
- Electric grinder or chisel

The batteries should be dismantled on heavy-duty tables at a height of at least 1 m. For large batteries, an island dismantling must be provided. Interlinked dismantling with roller conveyors is suitable for small batteries (hybrid batteries).

The aim of this AP for the IWF-TUBS was to perform a detailed design of an element of the dismantling system and to implement it as a prototype. After analyzing and evaluating the manual mechanical dismantling and the dismantling sequence, it seemed sensible to develop a gripper solution for the automated handling of the batteries.

In AS B.1.2, the requirements analysis and conceptual design of the gripper system took place. The mechanical design, the selection/design of the control hardware and software as well as the programming, assembly and commissioning were the subject of this AS. The description of the aforementioned development steps is summarized on the basis of the main subsystems and the functionalities of the gripping device. Figure B-14 shows an overview and the key individual components of the gripping device.

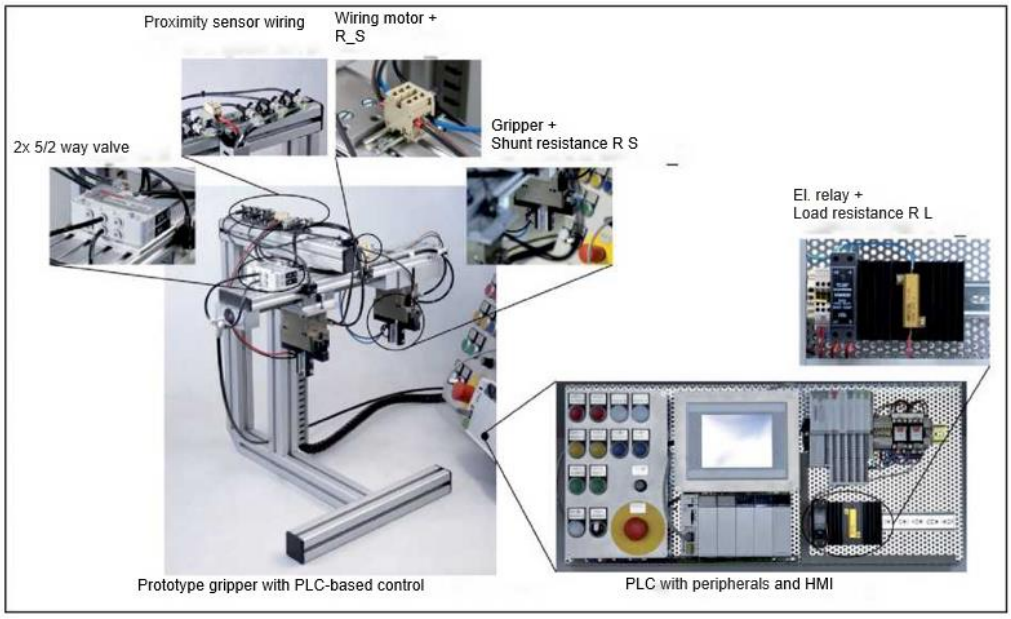


Figure B-14: Gripper system with individual subsystems and components

Gripper system

The gripper system consists of two coaxially arranged, pneumatically operated parallel jaw grippers from Schunk. Opening and closing can be detected by inductive proximity sensors. The grippers are controlled by two 5/2-way valves from Bosch Rexroth. The gripper jaws are made of PP due to the integrated functionalities and the necessary insulation from the battery to the gripper. An aluminum plate is screwed on from which the electrical cables for voltage measurement and the measuring resistor (shunt resistor R_S) also lead off.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Drive and linear axis: An IGUS linear axis with spindle and slide was used to adjust one side of the gripper. This axle is driven by a DC motor with planetary gearbox.

Support system: The mechanical components and the proximity sensors for positioning are attached to an ITEM profile rail. The entire system is also suspended from a profile rail structure to simplify test operation.

Control hardware: A modular PLC from Möller with digital and analog I/Os as well as remote I/Os was used in order to be flexible with regard to system changes and to have the option of integrating additional peripherals. To create a prototype, it also made sense to design a switch panel to test individual functions. A 5.7” touchscreen display was integrated into this panel as a human-machine interface (HMI). The motor is controlled through a relay circuit, the same applies to the load resistor R_L. However, an electronic relay was selected here due to the briefly high current flowing.

Voltage measurement and internal resistance determination: The voltage can be measured directly through the 0-10 V analog inputs of the PLC, as this voltage range is not exceeded by a lithium battery cell. The measured value is converted related to the resolution of the analog input (14 bit). As already mentioned, the internal resistance is determined by differential voltage measurement through time-dependent connection of a load resistor R_L. The voltage drop is measured through a shunt resistor R_S directly on the gripper jaw in turn through an analog input of the PLC. This improves the measurement result, as cable resistances and lengths have less influence on the measurement.

Software, operating concept and visualization: The gripper system is operated through a touchscreen display. The following functions are provided by the software:

- Manual gripper positioning
- Manual opening and closing of the grippers
- Automatic gripper positioning according to the inductive proximity switches
- Manual recording of the measured values
- Automatic recording of the measured values each time the grippers are opened/closed
- Visualization of the last ten measurement data voltage and internal resistance as a bar chart and colored classification into different ranges
- Display of the current voltage value

The software was created in accordance with DIN 61131 using the CoDeSys programming environment. The operating concept is illustrated in Figure B-15. Screenshots of the developed visualization and operation are shown in Figure B-16. Further technical details can be found in [Schmitt, 2011].

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

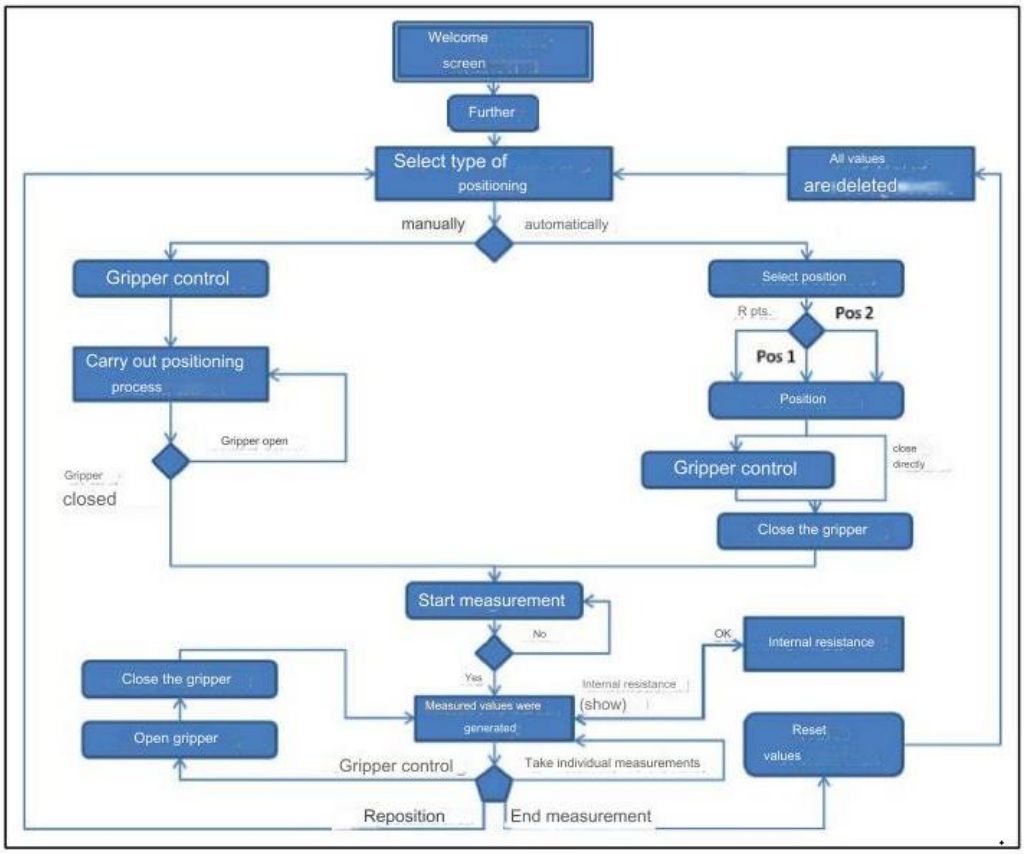


Figure B-15: Operating concept of the gripper system

Figure B-16: Screenshots of the visualization

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

B.1.5 Performing dismantling tests/testing

In the project, data and information relating to battery dismantling were structured and analyzed, taking into account assemblies, priority relationships, costs and a life cycle assessment with life cycle assessment. I+ME exchanged various information, e.g. on parts lists and assembly steps as well as CAD drawings, with TU-BS as part of **AP B**. Assemblies and battery components were cataloged and grouped in joint working meetings.

The project determined whether dismantling can be performed manually, semi-automatically or fully automatically. The recovered starting materials (lithium, electrolytes, metallic carrier foils) were evaluated with regard to reusability and new use, at least in the laboratory environment.

As part of the project, I+ME not only worked on the dismantling of battery systems manufactured in-house, but also dismantled an unknown battery system from a commercial vehicle manufacturer.

External access to the cell monitoring electronics (BMS) through RS 232 or CAN on the third-party system was not possible, and the dismantling of battery components by gluing or welding connections was correspondingly difficult. The pin assignment was unknown and could not be determined or could only be determined by reverse engineering, which was time-consuming.

Different vehicle batteries were dismantled to investigate the dismantling processes. The battery weights were between 35 and 220 kg per battery. The dimensions vary greatly and can be up to 2 m long and up to 1.5 m wide. The batteries are designed for installation in the vehicle trunk or as an underfloor battery. Due to the different battery systems, fully customized dismantling is not feasible. However, the majority of non-series batteries are currently being returned. It may therefore be possible to automate the dismantling process in the future if large numbers of similar batteries are produced.

Handling/preparation for dismantling

The dimensions and weights of the batteries require a dismantling area that must be accessible from at least two sides. A dismantling island (work table) has proven to be practical for the large batteries. This makes it possible to reach the screw connections and plug connectors, some of which are difficult to access, from all sides. For small batteries (e.g. from hybrid vehicles), a dismantling section, e.g. with a roller conveyor, is suitable. Here, the battery can be rotated accordingly and positioned manually for the work step.

The batteries should be transported to the dismantling sites lying on suitable wooden or plastic pallets. The batteries only have vehicle-specific mounting or load suspension options. This makes it necessary to transport them lying down on pallets wherever possible. Particularly with large and heavy batteries, there is a risk of the battery bending and causing a short circuit when lifting without a transport rack.

Dismantling

Standard tools are used for dismantling. However, any screwdrivers or wrenches used should be insulated. In the case of vehicle batteries installed on the underbody and exposed to moisture, the housing screws may be heavily oxidized, so that the connections must be removed destructively using a chisel or grinder. Two people should always remove a battery. This applies in particular to the large traction batteries, as the housing parts are so large that

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

they cannot be removed on their own.

Step 1: Removing the disconnect plug and voltage check

This step should be the first priority when dismantling such systems. On the one hand, removing the disconnector partially separates the circuits and reduces the voltage. Contacts are also available here to measure the voltage of the battery system.

Step 2 -Opening the housing

The housing parts can be connected with up to 100 screws. Screws are so close to the housing that angle attachments or very long extensions have to be used. Screwed-on brackets that were used for mounting in the vehicle must also be removed as they were usually screwed to the inner frame through the housing and the housing cannot be opened otherwise. For smaller batteries, screws usually have to be opened on all sides. The battery must be rotated several times

Seals are also glued in between the housing parts. Once all screws have been removed, the housing parts can be separated using assembly levers.

After removing the housing cover, the individual components of the battery system are exposed. The main part consists of the cells, which are usually combined into packs of up to 20 cells and make up 50% to 70% of the total battery mass. Depending on the battery design and size, a battery can contain over 100 cells. The battery also contains 5-8% of the total weight in cables, copper wires and electronics. Some batteries may also contain water or air cooling systems.

The further steps for dismantling are listed below. However, the sequence and procedure may differ for other designs. The main aim is to separate the cells and to separate the cell blocks from each other in order to reduce the electrical voltages in the system to safe values.

Step 3 - Removing the cooling system

Any existing cooling system covers connections and joints, so this must be removed first. An air cooling system consists of plugged plastic ducts and is usually easy to remove. In a liquid cooling system, openings in pipes for the cooling water system should be temporarily closed with adhesive tape or plugs to prevent residual liquids from leaking into the live system and causing short circuits.

Step 4 - Disconnecting the connections to the cell controller

Each cell has a separate connection to the cell controller. These connections are usually brought together as strands for a cell packet. If the electrical connections to the cell controller are disconnected, this can lead to overvoltages in the electronics and destroy them (fire hazard). To prevent this, the correct order in which the connections are disconnected must be observed. However, this requires more detailed knowledge of the circuit diagram or at least a numbering of the cell packets. If the plug connections on the cell blocks are disconnected starting with the highest number backwards to the lowest, overvoltage in the cell controller is avoided. The plug connections are manufacturer-specific plugs that can usually only be opened with special tools. It is difficult or impossible to open the plugs by hand when wearing gloves, so extreme care must be taken. If the plugs cannot be opened, the cables can also be cut. However, this must be done wire by wire, otherwise a short circuit will be created which will at least destroy the tool.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Step 5 - Dismantling the circuits

The next step is to unscrew the copper cables that connect the cell blocks, thereby interrupting the circuit. Exposed ends of the connections must be insulated with tape until final removal. Depending on the number of cells per cell pack and the internal connection (in series or series connection), further dismantling can now be performed relatively safely as the voltage per cell pack represents only a low risk (electrical, chemical).

Step 6 - Removing the cell packets

The cell packets are attached in different ways. On some models, the cell packs were fixed with retaining clips. No special tools were available to relieve the strain. The holding clips of the cell packs were therefore secured with adhesive tape and cut through using bolt cutters. The packets could now be removed and broken down into individual cells depending on the subsequent further processing.

Step 7 - Removing the electronics

Electronic components such as the control board and cell controller are installed in the battery. There is also extensive wiring and busbars between the electronics and the cells. As the plug connections are usually difficult to disconnect, most of the connections are cut with cable shears and the fractions removed.

Table B-8: Fractions after dismantling the batteries

Component	Origin/Material	Share [%]	Approx. value (€/kg)
Battery cells	*Unknown for used condition*	50 - 70	
Aluminum	Cooling lines/housing	1 - 4	1.20
Residual materials/waste	Rubber, adhesive tape, connectors, Velcro fasteners	< 1	-0.20
Plastics	Cooling lines, housing parts	0 - 3	0.00
Iron/metal parts	Screws, tension springs	1 - 2	0.15
Cables	Cables	2 - 6	1.50
Electronics	circuit boards	2.5 - 3.5	1.00
Busbars	Copper coated with plastic	0 - 3	3.80
Iron	Housing	18 - 44	0.15

To validate the gripper functionality “secure gripping of pouch cells with different formats” on the one hand and the integrated status determination on the other, tests were performed with three different cells. The test cells have different contact distances and geometries. The gripping of the batteries with the two parallel jaw grippers can be described as safe, whereby no lateral accelerations, for example due to robot movements, were applied. When designing the gripper, the gripping force was deliberately oversized due to the unknown installation conditions of the battery cells in the module, so that sufficient safety should be ensured. The

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

gripper jaws, which are currently made of a plastic with a low modulus of elasticity, offer potential for optimization; this leads to bending when gripping battery cell contacts with a thickness > 2 mm. A redesign using the material PEEK is being sought here. Furthermore, the thickness of the aluminum plates on the grippers can be reduced.

To validate the functionality of the in-process state determination, ten values for the tension were measured when gripping the respective test cell. The internal resistance was determined by connecting the load resistor for 3 seconds and the resulting voltage drop. This method can also be referred to as differential voltage measurement. Ten values were also documented here. The statistical evaluation of the data for the three pouch battery cells shows a low standard deviation (see Figure B-17) and thus the robustness of the method. The data was checked by ELENIA-TUBS in **AP A.4**.

Benefits of the integrated status determination with regard to dismantling: The motivation for integrating the voltage measurement and internal resistance determination was the fast and process-parallel recording of the battery status. The cell voltage and internal resistance were selected as characteristic values, as these can be determined during a handling cycle (< 5 sec.). The data obtained can be used to pre-assess the cells so that they can be sorted after the battery system has been mechanically dismantled. Voltage ranges can be defined, e.g. for the further use of the batteries, and conclusions can be drawn about ageing due to the internal resistance.

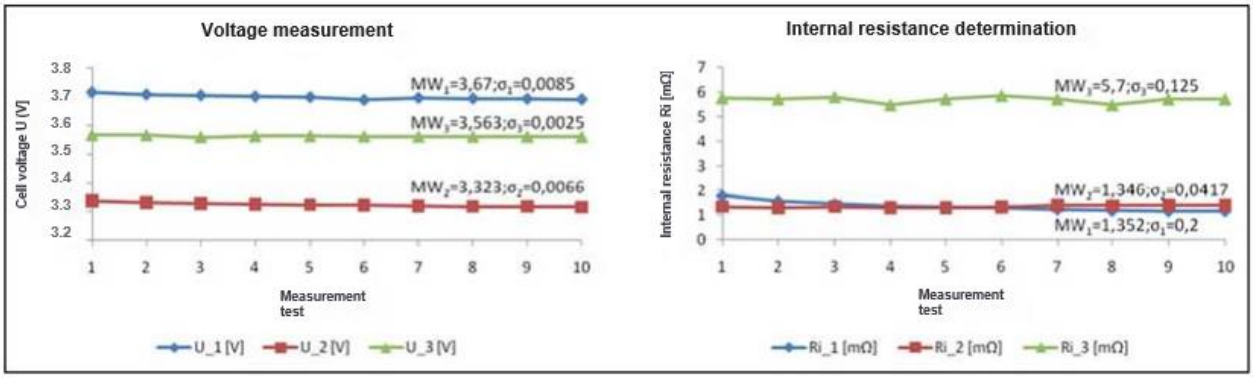


Figure B-17: Evaluation of the measurements

Final evaluation of the automation of dismantling:

In the preceding **AS B.1.2** to **AS B.1.4**, concepts for (partially) automated dismantling and dismantling system design were presented. The main obstacles to a high degree of automation are summarized here once again to illustrate the challenges of future work in the area of standardization.

Standardization: The last aspect is aimed at the diversity of variants in dismantling. As each declining battery system is in principle a separate variant due to the unknown life cycle, which is not subject to a uniform dismantling process, the design of automated systems is often not expedient, as the quantities for the amortization of these are not given. Furthermore, the number of variants increases with the number of manufacturers, product generations and designs.

Recommendations for action:

- Standardization of the geometric dimensions of the battery cells

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- Easy to dismantle connection technology.
- Modular design
- Accessibility of the connection points
- Minimize cabling

Environmental conditions during dismantling: The environmental conditions during dismantling require very specific automation solutions. Dust and dirt as well as undefined lighting conditions generally prevent the use of high-performance sensors, such as camera technology. The automated recognition of different battery systems or positions of individual components is difficult to realize and therefore the establishment of continuous automation is massively impaired. A change in these conditions can only be guaranteed by the intensity of quantities and a certain purity of variety, which in turn requires separate return concepts. Another way is to use systems that are programmed using special procedures, such as teach-in or play-back routines. For example, motion sequences are programmed by imitation, which are then executed by the automation devices. It is essential to design work processes that include manual activities as well as (partially) automated work steps (hybrid workplaces), although the aspect of occupational safety requires further detailed investigations.

Recommendation for action:

- Do not strive for “high-tech solutions” as long as the quantities do not absolutely require it
- Use of technology with change flexibility (e.g. simplified reprogramming)
- Establishment of hybrid workplaces

Training requirements: Automated production lines require highly qualified personnel to repair and maintain the plant technology. In dismantling, manual work with a rather low level of training and corresponding wage level is predominant. The dismantling costs would increase through the use of automated systems, as availability with regard to dismantling conditions would be difficult to achieve a satisfactory level. The same applies to (change) flexibility.

Recommendations for action:

- Hybrid workplaces
- Automation with an increased focus on flexibility in the sense of Convertibility
- Automation of individual recycling process stages (cell opening, etc.)

More detailed constructive recommendations for action are given below.

B.1.6 Derivation of requirements for a battery design suitable for dismantling and automation

The experience gained, recommendations and all conclusions were presented to the project partners in the working meetings as an interim status and discussed accordingly. The following are examples:

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- Modular battery system design
- No welded housings
- External communication plug
- Color-coded cells
- Tuning to cell shape standard
- Labeling of batteries with basic information
- Display of the charge status and battery status on the battery.
- Avoidance of different screw connection systems
- The need to use special tools to disconnect plugs or disconnect connections should be avoided.
- No glued, riveted or soldered connections of parts that have to be separated for dismantling.

The derived requirements were passed on to the project partners involved, who forwarded them to the relevant contact partners in the R&D/product development department within the company.

Important suggestions and findings were presented, communicated and discussed at an early stage as part of LithoRec's public relations work and through the membership of individual project partners in the National Platform for Electromobility.

Experience shows that automated dismantling or cell removal is not technically possible with the battery systems currently available. Extensive plug connections, cooling lines and retaining clips must be removed to reach the cells. Cell removal is then only an insignificant part of the work.

The product analysis performed in **AS B.1.1** resulted in requirements for the ease of dismantling of the battery systems. The aim is to standardize the connection types (e.g. screw connections or clip connections) and also the specifications of the individual connection types. For example, the use of hexagon socket screws in combination with Phillips screws or internal star screws leads to an increased need for tool changes. This is also the case if similar screws of different sizes make a tool change necessary. In principle, it can be said that in the product planning phase, the

The basic principles of design for dismantling, design for recycling and design for the environment should be observed so that the effort involved in dismantling the battery systems can be kept to a minimum and the costs for dismantling remain low throughout the entire process chain. In addition to the connection types already mentioned, the simplest possible building structure and the selection of as few different materials as possible should be mentioned here as examples from Design for X.

With regard to automation capability, it can be said that criteria related to the dismantling process, such as the complexity of a dismantling movement, safety-related criteria, such as

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

the distance to a potential, but also part-related criteria (e.g. part weight in kg) and economic criteria, such as the urgency of automation, should be taken into account as early as the planning stage of the battery systems. The criteria presented in **AS B.1.2** can then be used to create automation concepts or partial automation concepts.

Previous investigations have also shown that it will be necessary for certain information on dismantling the battery systems to be provided by the manufacturer. It is therefore necessary to provide information on harmful substances that could interfere with the recycling process and safety information for dismantling, such as the sequence of plug connections to be disconnected, in order to prevent damage to the cells.

B.2 Treatment and utilization of electrolytes

The treatment and recovery of the electrolyte is an important part of the recycling process for lithium-ion batteries and is performed in cooperation between the IPC-WWU and the recycling company FRZ. Recyclable materials that can be recovered are solvents (EC, DEC) and conductive salts. Due to the high reactivity of the electrolyte salt to water (humidity) and the associated difficult and costly handling when opening the cells, safe opening concepts must be developed as a first step. To this end, the IPC-WWU is developing two alternative concepts which, in addition to safety aspects, ensure subsequent recovery of the lithium salts (method development for $LiPF_6$) in a distillation process (**AS B.2.3**) with subsequent recrystallization (**AS B.2.4**). In a further step, IPC-WWU will investigate the process development for recovering the lithium salts and solvents.

B.2.1 Development of opening concepts

The initial aim of **AS B.2.1** is to develop concepts for the safe opening of lithium-ion batteries that enable the electrolyte to be processed and recycled. Two opening concepts were pursued, which can also be optionally combined:

1. Opening under inert gas conditions

A fire and explosion-proof environment is created by the inert gas. However, the electrolyte is present as a fluid, which makes handling more difficult when separating the cell housing from the separator/electrode assembly and can reduce the yield during electrolyte recovery.

2. Opening under refrigerated atmosphere

The battery systems are cooled to approx. -60°C before opening in order to prevent highly exothermic reactions (risk of fire and explosion). The cooled batteries are then opened and the housing is separated from the other battery components (electrodes, separator, electrolyte).

Finally, these two concepts are to be combined in order to achieve the best possible recovery.

The cell to be opened is discharged with the aid of a resistor in the IPC-WWU.

Some cells were deep-discharged to check for any copper deposits on the cathode. Using ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometry), no copper could be detected in the corresponding materials. The discharged cell is then inserted into a glove box. For the further dismantling of the cell, it is important to remove the conductive salt present in the cell as completely as possible, especially with regard to safety aspects and the processing

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

of the electrolyte. For this purpose, approx. 25 ml of dimethyl carbonate is injected using a cannula. The injected dimethyl carbonate is distributed by moving the cell (15 minutes). The solution can then be drawn off with a syringe and transferred to airtight sample containers for further work steps. Once the cell has been ejected, it can be opened using a suitable tool.

The electrode stack is exposed through a U-shaped incision in which the current arresters remain untouched. After exposing the stack, the current arresters near the electrode stacks can be cut one after the other.

Care must be taken to ensure that the current arresters of the anode and cathode are not cut at the same time and that the electrode stack is not damaged during cutting, which could result in a short circuit. The electrode stack can now be removed and disassembled into its individual components (see Figure B-18).

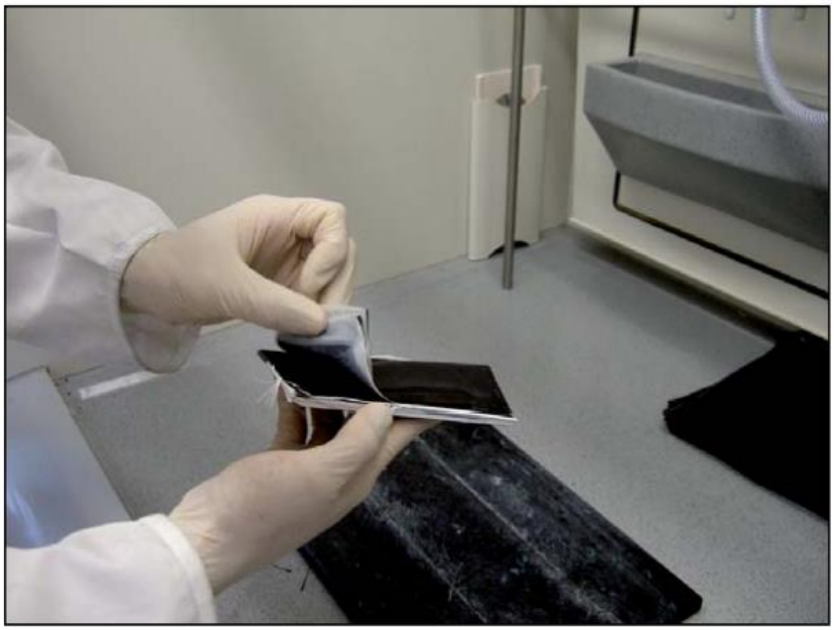


Figure B-18: Electrode stack (IPC-WWU)

The opening concepts for the laboratory scale were continuously optimized on over 100 cells. The opening was also performed in a glovebox under inert gas. This method showed the same results as opening in a fume cupboard. Frozen atmosphere opening was tested by freezing cells with liquid nitrogen and then opening them either under inert gas atmosphere in the glovebox or in a fume hood. For the laboratory scale, however, it has been shown that the opening is completely sufficient under a frozen atmosphere. Sudden ignition of the material etc. can be extinguished quickly and easily with liquid nitrogen.

B.2.2 Draining the wet battery cell

A key aspect of this work step is the yield of the subsequent electrolyte recovery. The concepts to be developed for draining the wet battery cell should aim to prevent decomposition of the electrolyte, taking safety aspects into account, in order to achieve the highest possible yield in the subsequent reprocessing process.

The previously separated individual components (**AS B.2.1**) are washed again with dimethyl

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

carbonate and then dried. Drying is achieved by storage in a waste or a glovebox, which was completely sufficient for these purposes. The individual components were vacuum-packed for transportation.

B.2.3 Process development of a suitable distillation process for electrolyte recovery

In **AS B.2.3**, central attention is paid to the recovery of the valuable lithium salts of the electrolyte. In a first step, the IPC-WWU is establishing a distillation process for gentle distillation of the electrolyte for this purpose. The FRZ is testing the establishment of the distillation process in practice and is recovering the first electrolyte liquids using a suitable liquid separation method to be selected and installed. The selection and suitability of the device to be procured is based on the results of the IPC-WWU. The electrolyte contained in the separator/electrode composite is removed at an elevated temperature in a vacuum, collected in a cold trap and recovered by distillation. The distillation process to be developed by the IPC-WWU and the subsequent recrystallization are to be examined by FRZ for technical feasibility with the aid of condensate separators for collecting the liquids. The different processes must be compared and evaluated by FRZ with know-how input from the IPC-WWU on the basis of technical feasibility, the yields achieved, the materials used and their energy balance.

The distillation results showed that the conductive salt was still present in all fractions. The investigations were performed using inductively coupled plasma with optical emission spectroscopy.

Furthermore, decomposition of the conductive salt and the organic carbonates (decomposition into e.g. EMC, see Figure B-19) occurred due to the temperature.

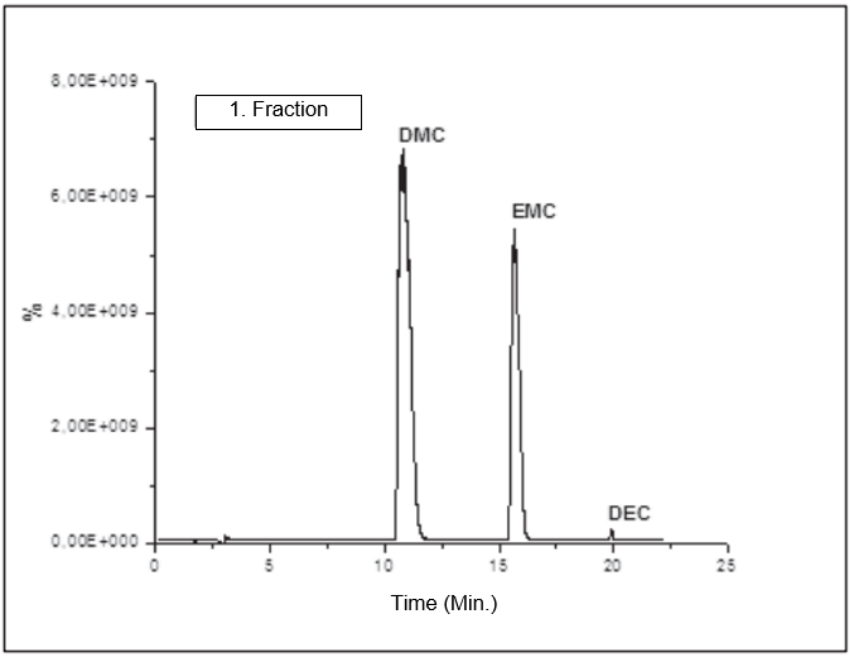


Figure B-19: Analysis of the 1st fraction of the distillation process using GC-MS (IPC-WWU)

In addition, the various organic carbonates could not be completely separated from each other

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

by distillation, as can be seen in Figure B-20.

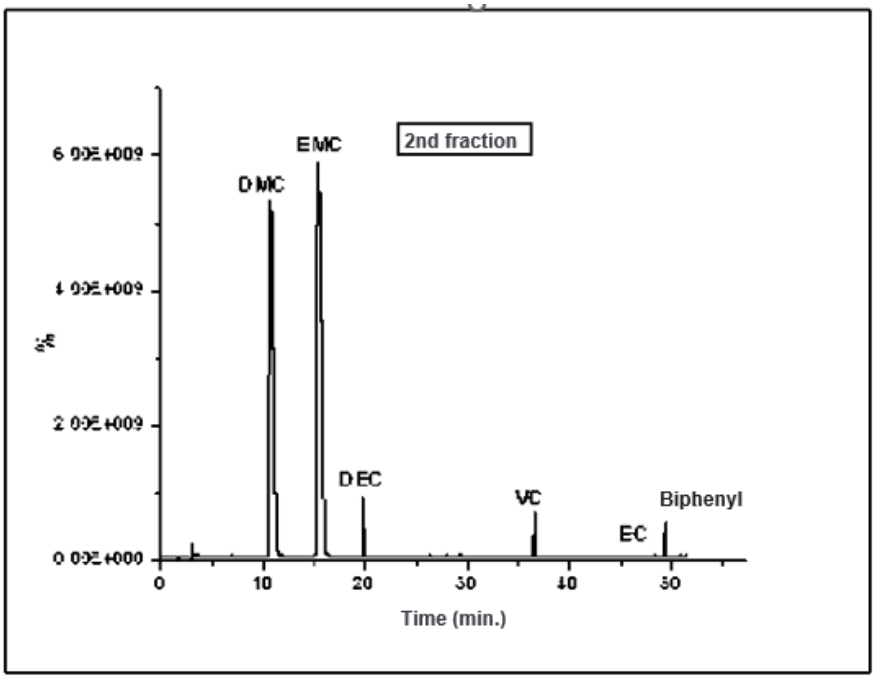


Figure B-20: Analysis of the 2nd fraction of the distillation process using GC-MS (IPC-WWU)

The distillation process for electrolyte recovery must therefore be examined more closely and suitable alternatives sought in parallel. Extraction with supercritical CO2 offers a promising alternative and initial tests within the project were very promising.

B.2.4 Process development of alkaline recrystallization of the conductive salts

It is known that the chemically very related potassium hexafluorophosphate (KPF 6) can be recrystallized from hot alkaline solutions. Therefore, **AS B.2.4** examines two essential process steps for the recrystallization of LiPF 6 from this solution. These are:

- Dissolving the LiPF 6 using a hot alkaline solution
- Recrystallization of LiPF 6

Since the conducting salt could not be separated from the electrolyte by distillation (**AS B.2.3**), the recrystallization step was omitted, as the prior decomposition of the conducting salt makes recrystallization and purification obsolete.

B.3 Mechanical, thermal and chemical processing of the individual components

B.3.1 Dismantling the dry cells and sorting

At IPAT-TUBS, example cells were manually disassembled to determine the composition of the individual cells for scientific monitoring of the EC. The mass fractions of the electrolyte, the copper foil, the aluminum foil, the cathode and anode coating, the separator and other cell components, such as the cell envelope, were determined.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The cells must first be checked for electrical charge and discharged if necessary. When handling electrolyte, consisting of highly flammable and sometimes irritating solvents, e.g. Mixtures of diethyl carbonate, dimethyl carbonate and ethylene carbonate, as well as the conductive salt lithium hexafluorophosphate, safety measures such as wearing protective clothing, safety goggles, butyl rubber gloves and processing under a suitable fume hood must be taken. Furthermore, sparks must be avoided when opening the cell casings, some of which are quite solidly made, as the highly flammable electrolyte solvent could otherwise ignite.

It quickly became clear that manual dismantling and thus possible manual dismantling and sorting of the cells, taking safety measures into account, was not economically viable. As described by EC, the existing preparation technology was used for a more realistic view of the dismantling processes.

After coarse crushing of a rotor shear, the separator could be separated by air separation. Further fine comminution in a cutting mill made it possible to separate approx. 80% by weight of the electrode coating. To recover the remaining 20%, the findings from the downstream **AP B.3** must be applied. A complete separation of coating and carrier films by type is thus possible in industrial applications.

B.3.2 Processing and recycling of cell housings, separators and metallic components

Automated cell decomposition:

A double-rotor shear was used for mechanical cell decomposition. In this machine, materials are shredded by cutting stresses. The cutting unit of this machine runs slowly, which keeps wear to a minimum.

The dismantling tests were performed with complete battery cells, which were previously discharged to below 3V. The cells were placed individually in the double rotor shears. In the shredding machine, the cells were cut into units with grain sizes ranging from 1 to 8 cm. The mixture of electrode foils, housing parts, separator and electrolyte can then be dried and passed on to the downstream processes.

Processing and recycling of cell housings, separators and metallic components

This work item of the project deals with the processing of the dismantled components, such as cell housings, separators, metallic contact components and sealing materials.

The composite of current collector and electrode coating (electrode, anode and cathode) should be transferred to work steps **AS B.3.3** to **AS B.3.6** for further processing as a whole or in already shredded units. To this end, EC examined the influence of different comminution techniques and degrees of comminution on the subsequent processes. The general aim is to process and recover the active materials and to obtain the purest possible copper and aluminum foil. The tests performed by EC on the reconditioning of lithium-ion batteries were performed with battery cells that had previously been dismantled and dried. The aim of these processing tests was to separate the active materials and to obtain the purest possible copper and aluminum fraction. Various comminution techniques as well as sieving and density sorting methods were used for these tests.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Preparation tests:

Shredding tests were initially performed with complete battery cells (pouch cells) in a laboratory granulator with a 10 mm screen basket. After comminution, the ground material had a particle size of less than 10 mm.

The evaluation of two comminution steps and sieving in conjunction with separation techniques resulted in a recovery of the active material of approx. 40% of the feed mass. Approx. 53% was present as copper and aluminum fraction and approx. 7% formed the fraction of the separator material. Copper and aluminum particles are now still present as a mixture. The surfaces of these metal foil particles are still partially coated with active material and graphite, which makes it difficult to separate them into a clean aluminum and copper fraction. At this point, the metal particles should be cleaned again (IPAT- TUBS), whereby the active material and graphite coating is removed and clean aluminum and copper particles remain.

The mixture of clean aluminum and copper foil particles can then be separated by type using density sorting processes. The metal foil particles (Al, Cu) must then be converted into a suitable form for further use in the raw materials industry. The film particles must be converted into material particles of a defined shape and size using a briquetting press. This is the only way to use these metals in a smelting or blast furnace process.

Further processing tests were performed with battery cells that had previously been dismantled and dried in a double rotor shear. Cells with solid housings (Fe, Al) and connection contacts were used. The first step in processing these cells was to remove the shredded housing parts and connection contacts from the remaining good flow. This step is necessary because these stable, solid parts would damage the screen inserts of the subsequent shredding units. The casing parts were removed from the remaining material flow either with the aid of a magnet (Fe casing) or by means of heavy part discharge by cross-flow separation (Al casing).

The resulting material mixture of aluminum and copper foil particles with active material coating as well as separator material and some insulation sheaths were also further processed in the manner described above. A large amount of active material was also separated from this material and a clean aluminum and copper foil fraction was produced.

Different cell types (round cells, prismatic cells, pouch cells) were processed. According to the available results, the average yield in relation to the total mass (incl. electrolyte) of the cells:

Copper	approx. 11%
Aluminum	10 -15%
Coating material of anode and cathode	ca. 50%
Iron (only for iron-coated cells)	10%
Waste (separator, plastic films)	ca. 3%

B.3.3 Process development for the dry separation of active materials from the current collector

AS B.3.3 deals with the development of processes for separating the coating materials, which contain the valuable components Co, Ni and Li in lithium metal oxides, from the current collector foil (Al, Cu). Separation of the current collector foil and active material is essential for

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

the subsequent hydrometallurgical processing of the active material, as the Al current collector foil, like the active materials, dissolves in an acidic environment and thus significantly disrupts the processing procedure. Since the active material is not completely separated from the current collector films during the mechanical opening and separation of the battery cells, it is of great importance to examine the separation step of active material and current collector film separately once again.

Dry separation

Based on the results of a process screening, processing with the granulator was selected for parameterization. The process and physiochemical parameters such as rotor circumferential speed, rotor design (disk and cutting rotor), temperature control of the process chamber (cooling) and pre-treatment of the ground material by drying or cooling with CO_2 snow were varied. In addition, a further process step for deagglomeration was included in the recycling process chain, which enables the direct production of electrodes from the recycled material mixtures (in particular non-cyclized electrode scrap from production) and thus direct further processing of the detached coating powder. The method developed is suitable for all types of electrodes to be tested in LithoRec (cyclized, non-cyclized and scrap electrodes) and is used for other products in the following according to the work plan.

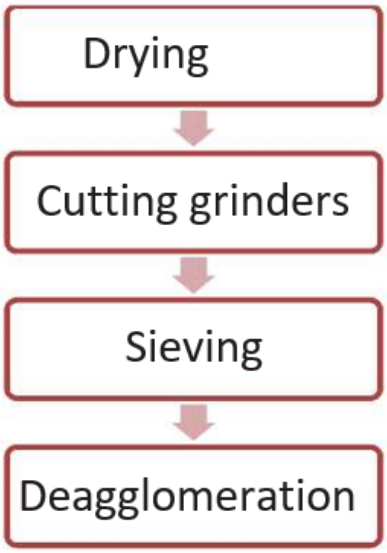


Figure B-21: Process flow diagram of dry separation

Drying of the electrode units moistened with electrolyte solvent at moderate temperatures is followed by a grinding step in a cutting mill. Current collector film and coating powder are separated by screen classification. The resulting powders are then deagglomerated in an impact mill.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

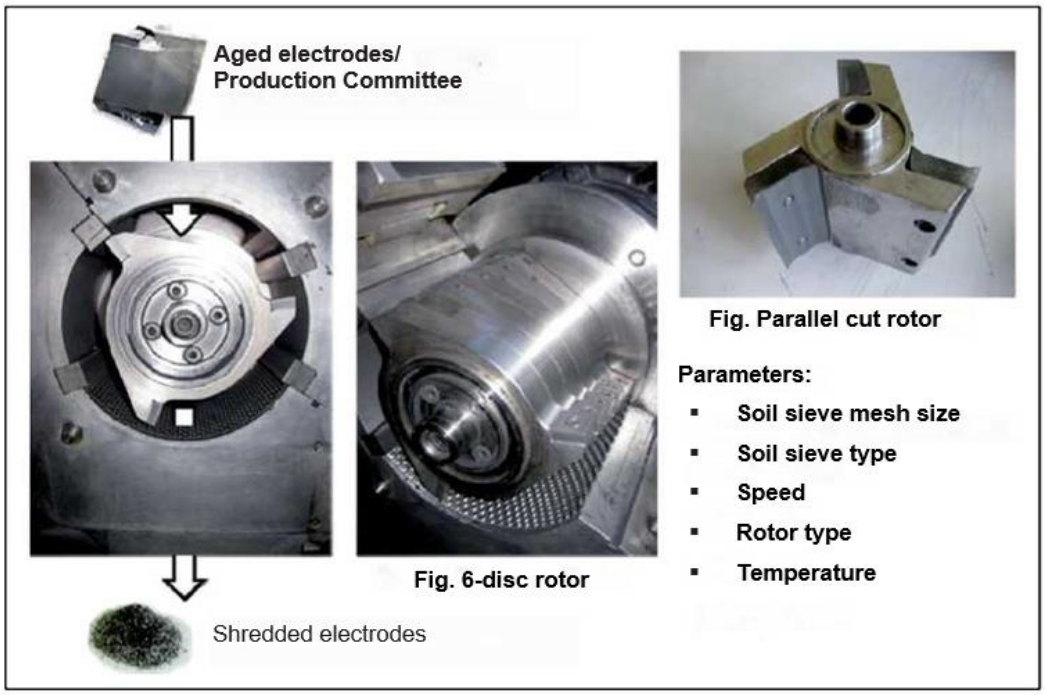


Figure B-22: Mechanical separation in the granulator

Influence of the circumferential rotor speed u

Figure B-23 shows the proportion of fine fractions after screening of the cutting regrind from the electrode scrap as a function of the rotor peripheral speed.

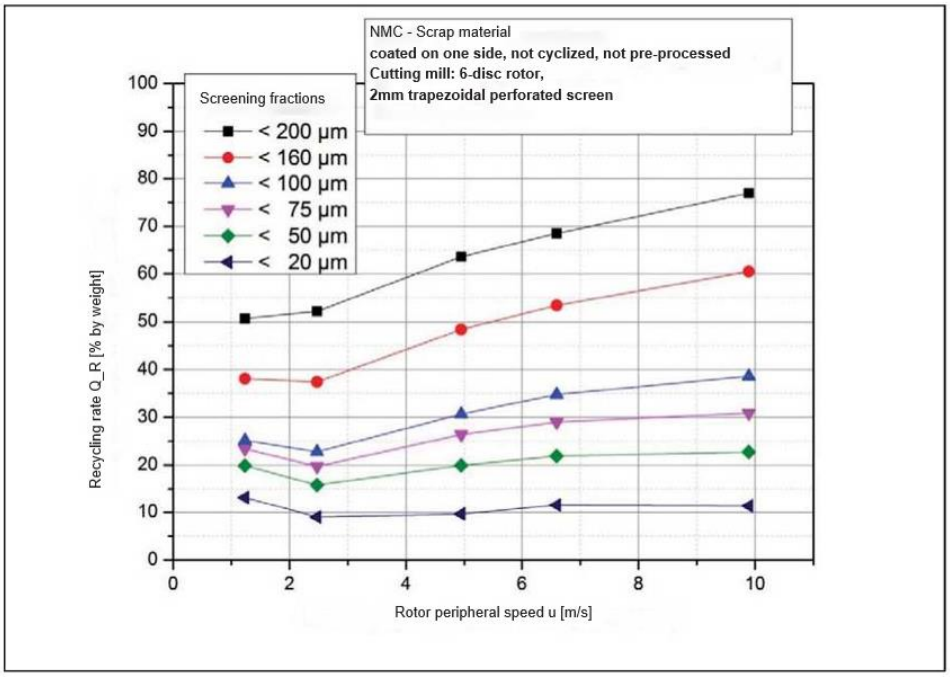


Figure B-23: Proportion of fine fractions after loading in granulators at varying rotor speeds for classification (screening) with different separation particle sizes (6-disc rotor, 2 mm trapezoidal perforated screen)

An analysis of the fine fraction using atomic absorption spectrometry showed that the

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

detached coating accounts for 99% of the fine fraction. It can be seen that the proportion of the fine fraction increases with increasing speed. For this reason, the maximum number of revolutions possible with the granulator was initially selected for further tests. For this process parameter, investigations of the aluminum content revealed varying contents in the fine fraction x < 200 µm. Mass fractions between 0.7 wt-% and 1.0 wt-% were determined using atomic adsorption spectroscopy (AAS). Since increasing the rotor speed increases the fine fraction and thus the recycling rate, but the aluminum contamination does not increase at the same time, an increase in the cutting mill speed is of interest for subsequent investigations.

Assessment of the dry recycling process

The introduced process for mechanical separation can be realized on an industrial scale with little equipment and low running costs. In addition, recycling rates of up to 91% by weight of the coating material on the electrodes fed into the process are achieved. Another process variant currently being patented achieves a pure separation of over 99% by weight of the cathodic active material. On the one hand, measures will have to be put in place to protect against and remove dust. On the other hand, no additional solvents are needed in the dry process, which would require personal and environmental protection measures, might have to be separated again in an energy-intensive process or would contaminate the intermediate product.

According to the results from **AP C.3**, aluminum contamination is not an obstacle to direct and repeated processing into electrodes (recycling of electrode scrap). In the hydrometallurgical recycling process developed by CM, concentrations > 1 wt.% are classified as critical due to the potential formation of oxyhydrogen gas. Furthermore, aluminum impurities negatively influence the process of new synthesis of active materials from transition metal salt solutions in HCST. On this basis, the processes and the recycling strategy can be specifically parameterized and the maximum tolerable aluminium content for the two recycling types can be set. As a result, a further separation step or one that is an alternative to screening may be selected, which can result in additional investment and operating costs. This process is currently being patented and ensures that contamination with film particles is reduced to less than 0.1% by weight. Assuming that the reconditioned powder (scrap material) can be processed directly into electrodes - with or without the subsequent addition of inactive electrode components - the process of recycling the uncycled scrap materials would be economical, as revenues of €55/kg NMC multiplied by the NMC content of the recovered powder would be offset by manageable costs.

As a preparatory step for hydrometallurgical processing, a separation step that separates the coating and current collector foils with > 99% purity is also elementary. In addition to the increased yield in the active material area, the effectiveness of subsequent process steps is increased as metallic impurities do not have to be laboriously removed later on. Furthermore, pure aluminum can be reprocessed and the copper can also be further processed without impurities.

The step of separating cyclized coating materials from the stream collector can also be performed as a single process step on a large scale and can therefore be designed economically. The upstream steps, in particular the dismantling of battery systems, modules and cells down to the cell component level, are therefore crucial for the process of conceptual battery recycling.

This AS was based on results from preliminary tests on extractions of commercially purchased

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

NCA and LFP. These basic principles were transferred to the work provided by IPAT-TUBS within this AS and further elaborated.

The focus of this AS was to analyze and test the usability of the cathode materials provided by IPAT-TUBS using hydrometallurgical methods.

The cathode materials used were NMC from formed cells and as rejects in the form of NMC applied to the aluminium current arrester and LFP from cyclized cells. The materials were obtained as part of this AP using granulator and sieving processes. The input material analyses were performed by Chemetall's analytical laboratory. The analyses focused in particular on the aluminum content and the general chemical composition of the materials. Among other things, this made it possible to detect cross-contamination of the cathode material, for example due to tool abrasion during the granulator process. In further work, the cathode materials were hydrometallurgically processed using acidic, oxidative or reductive media and the amount of lithium recovered was analyzed.

After extraction of the materials, the processing of the extraction solutions was tested using precipitation reactions in order to subsequently produce pre-purified solutions containing lithium salts, which must be suitable as a basis for subsequent ion exchange to produce high-purity solutions.

The AS thus provided CM with important findings on the hydrometallurgical processability with subsequent processing of the materials provided; at the same time, the results served IPAT-TUBS as an indispensable reference for the targeted continuation of work on the dry separation of the active materials from the aluminum current collector.

B.3.4 Process development of the wet mechanical separation of the electrode coatings from the current collector and their mechanical separation

The wet-chemical separation of the electrode coatings is based on the dissolution of the composite structure of the coating by dissolving the binder polyvenylidene fluoride (PVdF) in the solvent N-methyl-2-pyrrolidone (NMP). In contrast to the introduction of mechanical energy in purely mechanical separation, the chemical solution reaction is used as the process principle here.

In the process development step for the wet-chemical separation of the electrode coatings from the current collector and their mechanical separation, a process for separation was developed, elementary observations on the process were made and process parameters, such as the choice of solvent, temperature, size of the feed unit, stirrer circumferential speed and separation grain size, were identified and varied. After further processing in **AS B.3.5** by iPAT-TUBS, the separated coating was transferred to the CM for further hydrometallurgical processing in **AP B.4** and used as reconditioned material in **AS C.3.3** by iPAT-TUBS and LTA. Both processes were successful.

The wet-chemical process developed at iPAT-TUBS consists of the process steps shown in Figure B-24. First, the electrodes were roughly pre-cut so that they could be stirred better in the next step. This was followed by dissolution in stirred solvent N-methyl-2-pyrrolidone for 20 minutes at a temperature of 90°C. After sieving the foil units through a 50 pm stainless steel sieve, the solution was centrifuged. The sediment was dried at 140°C, ground and deagglomerated to a homogeneous powder in an impact mill. As the mortaring step is not

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

required if suitable drying methods are used, for example spray drying, it was not included in the flow diagram.

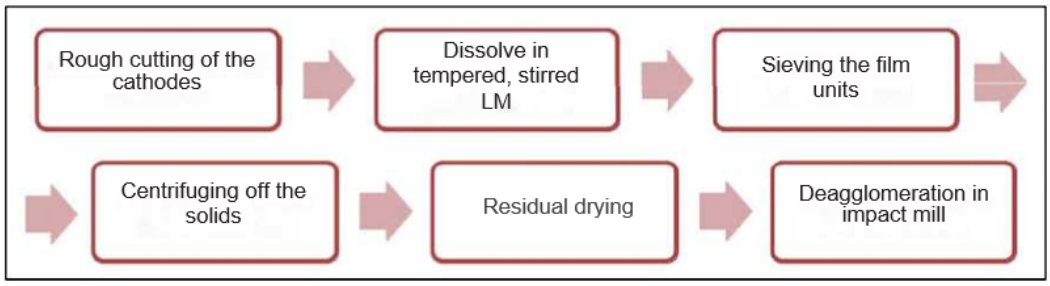


Figure B-24: Process flow diagram wet chemical separation of the coating of battery electrodes

The proportion of recycled coating is currently 95% by weight. Furthermore, after further processing by iPAT-TUBS in **AS B 3.5**, a particle size distribution that is suitable for coating and further hydrometallurgical processing is achieved, which is very similar to the original particle size distribution of the starting materials. The residual aluminum content was determined to be approx. 0.06% in a preliminary test using atomic absorption spectroscopy.

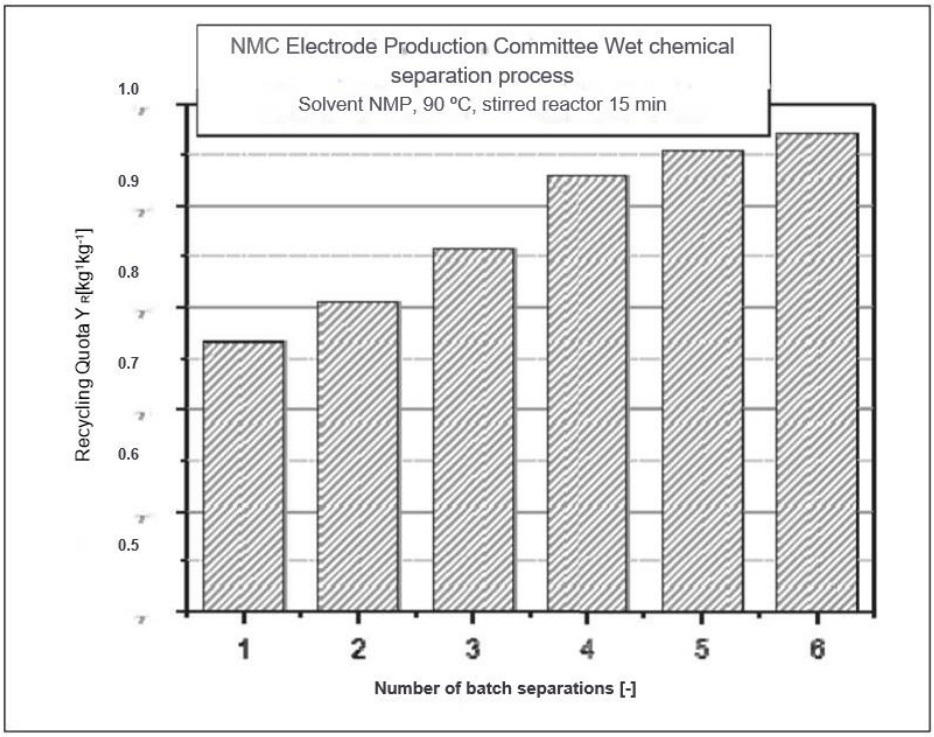


Figure B-25: Recycling rate over number of batch dissolving processes

Figure B-25 shows how the proportion of coating recovered in relation to the mass of coating applied, referred to below as the recycling rate, changes with the number of batchwise dissolving processes. The continuous increase from a recycling rate of 76.5% by weight after the first processing to 97% by weight after the sixth processing cannot be explained by the actual dissolution process, but rather by process-related inadequacies in the batchwise solid/liquid separation. As the liquid level drops during screening, the suspension wets the remaining units of film at the film/liquid interface.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Active materials and residual solvents remain, especially between the units of film. This effect can be prevented by recirculating filtered solvent. The liquid level would not drop and, in addition, pumped solvent would flush the units of film through a shear flow (see Figure B-26).

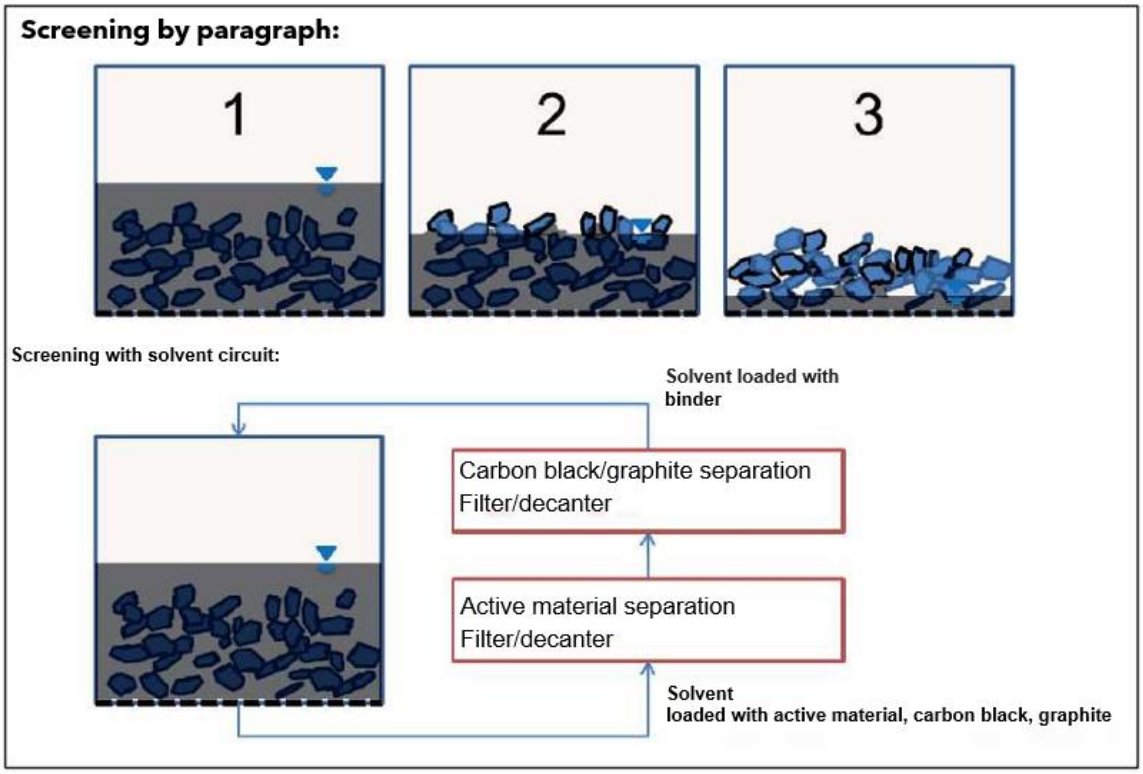


Figure B-26: Batch filtration operating mechanism (top), operating mode with solvent circuit (bottom)

In addition, the alternative process steps shown in Figure B-27 to the operations shown in the upper part of the figure were identified for wet chemical separation.

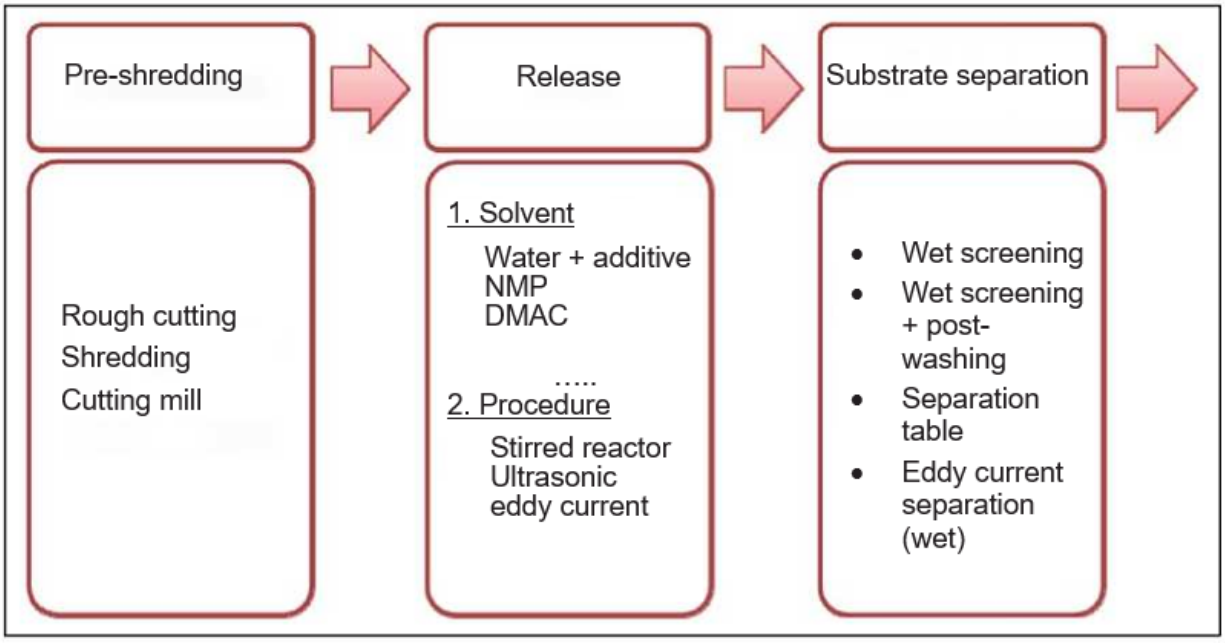


Figure B-27: Process flow diagram of process alternatives for wet chemical separation of the coating of battery electrodes

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

As part of this AP, cathode materials were provided by iPAT-TUBS, which underwent a “wet” separation. In this case, the extraction of the binder with organic solvent was investigated. This should ensure that the current leakage foil is removed gently. The samples were analyzed in Chemetall's analytical laboratory and then extracted and processed in the preparative laboratory.

The samples had significantly lower aluminum contents than the dry separated samples and showed the same extraction behavior.

However, it should not be forgotten that the handling of organic solvents is subject to many regulations (explosion protection, VOC directive, etc.) and should therefore be avoided wherever possible. Furthermore, the cathode materials should ultimately no longer contain any organic solvents before further processing, which makes further drying necessary.

For this reason, it was decided in consultation between CM and IPAT-TUBS to avoid separation with organic solvents wherever possible.

B.3.5 Preparation of highly concentrated, particulate active material suspensions

The aim of this step is to further process the resulting active material suspensions in order to obtain a product that can be further processed hydrometallurgically and to be able to directly recoat the active material obtained.

Centrifugation was first tested to concentrate the suspension. This process has proven itself on a laboratory scale and was the simplest method for quickly preparing the separated coating for further processing steps. However, concentration by centrifugal separation can also be transferred to an industrial scale. In this case, a scale-up of the determined separation parameters to a decanter would be an option.

The use of a frame filter press is difficult on a laboratory scale due to the aggressive solvent NMP, but is conceivable on an industrial scale. An initial concentration during the circulation pumping of the solvent proposed in **AS B.3.4** by means of a porous filter cartridge or cross-flow filtration is conceivable.

For further processing of the dried wet-chemically separated coating and the physically separated coating, iPAT-TUBS introduced deagglomeration in an impact mill. This innovative step makes it possible to apply the resulting coating directly to a carrier film using a standard coating process without agglomerates that interfere with the homogeneity of the coating. On the other hand, deagglomeration facilitates downstream hydrometallurgical processing by CM.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

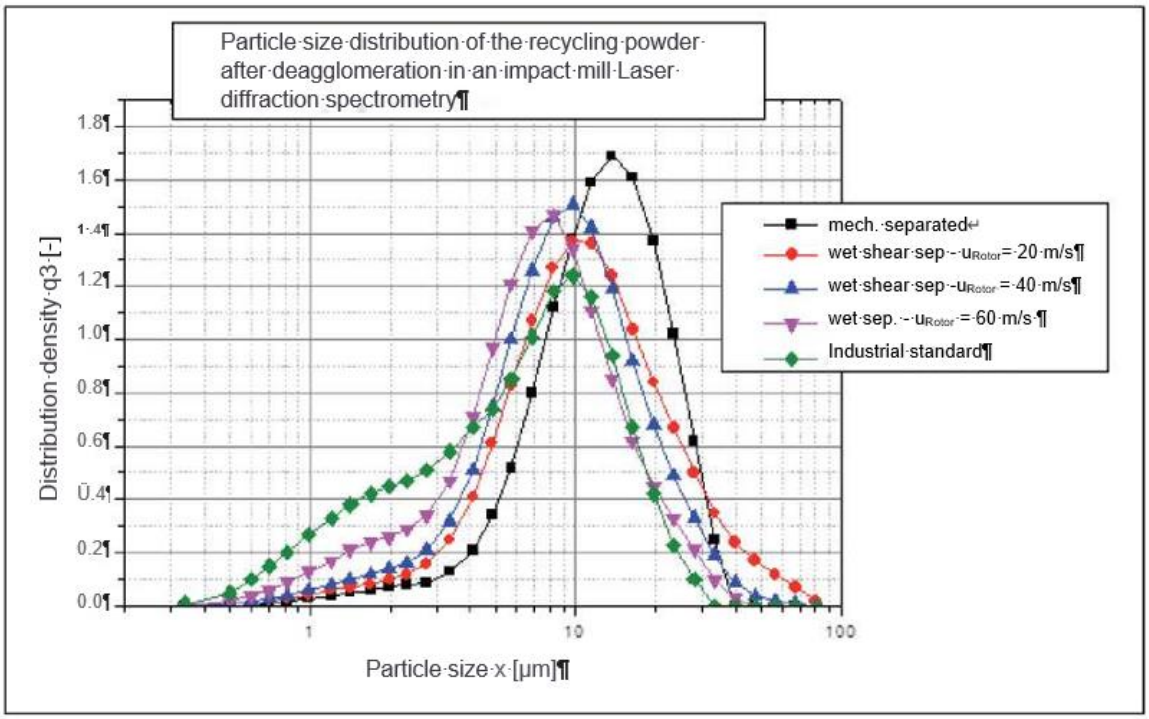


Figure B-28: Particle size distribution of the recovered coating after deagglomeration in impact mill

The alternatives identified for concentrating and further processing the recovered coating are summarized in Figure B-29.

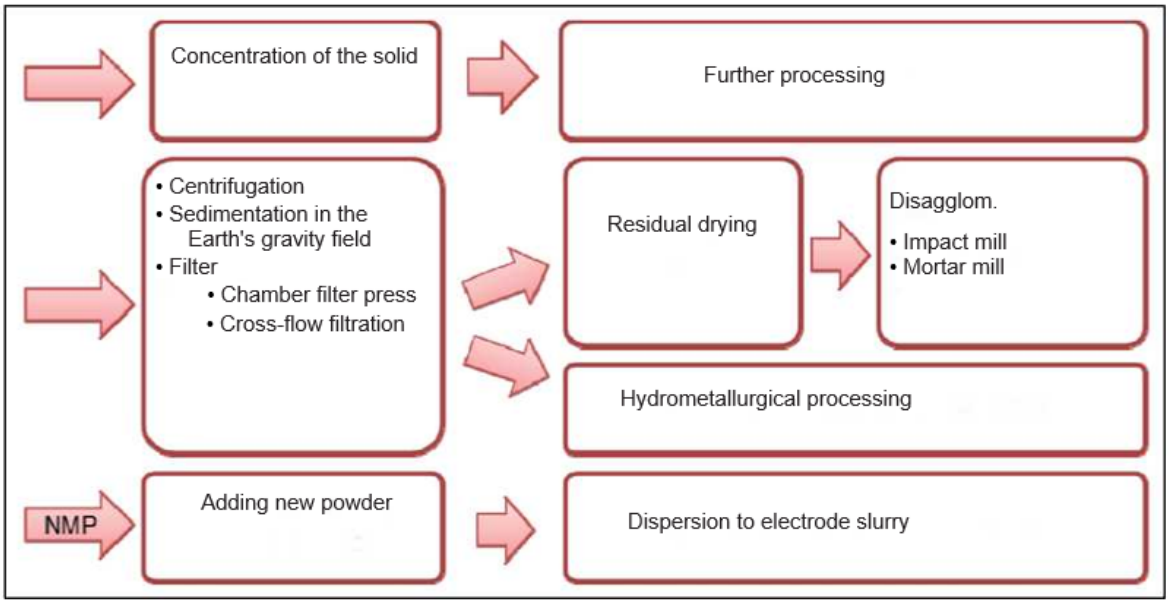


Figure B-29: Concentration and further processing after wet-chemical separation

The production of the solid suspensions provided by CM in this AS was performed by IPAT-TUBS. Depending on the processing methods, the suspensions produced from NMC and LFP from various sources (rejects as well as formed and cyclized cells) as well as cyclized NCA had different average particle sizes. The input material was analyzed in CM's analytical laboratory, focusing initially on the general chemical composition. In the case of material samples from graphite anodes, the copper content and the lithium content were also of particular interest; in the case of samples from cathode materials, the copper content and the

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

lithium content were of particular interest.

One of the main concerns was the metallic aluminum content and the presence of cross-contamination of the material, which is possible due to the mechanical processing by IPAT-TUBS.

This AS focused on the question of what influence the morphology of the particles and the particle size have on the recovery of the raw materials, i.e. to what extent a change in the reaction behavior of the materials was observed during extraction. Parameters of particular interest here were the suspendability of the materials in the extraction medium, the behavior during extraction, such as the tendency to foam, and the influence of the materials on the extraction speed and recovery rate. The results were communicated to IPAT-TUBS and were incorporated into further process developments in the production of the materials in the form of solid suspensions.

B.3.6 Extraction of binder systems from electrode materials depending on the separation alternatives

In **AS B.3.6**, extraction processes were developed to remove the binder systems from the electrode materials as a function of the separation alternatives in order to investigate the reusability of the binder systems.

The work step of extracting the binder systems from electrode materials depending on the separation alternatives has been completed as planned. The binder is extracted by the solvent NMP in **AS B.3.4** and can be used again as a binder formulation without requiring further processing. For this purpose, the binder content of the slurry/solvent is determined by thermogravimetric analysis and the binder, active material and additive content is increased to the desired composition by the targeted addition of the respective ingredients.

In purely mechanical separation, binder extraction for direct reuse as a coating or admixture material is not necessary, as it has been proven on coatings made from reconditioned scrap materials that the binder is still fully functional. For this purpose, adhesion tests were performed on the recycled cathodes, which showed an adhesion between the current collector foil and the coating that was comparable to that of new electrodes. The binder also proved to be non-disruptive during further hydrometallurgical processing at CM.

B.4 Hydrometallurgical processing and recycling of non-ferrous metals

The aim of this project was to recover non-ferrous metal recyclables from HEV/PHEV/EV lithium-ion batteries, in particular lithium and transition metals. Pilot plants were to be set up at the Langelsheim/Harz production site for these processes to be developed or optimized in order to test their practical feasibility.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

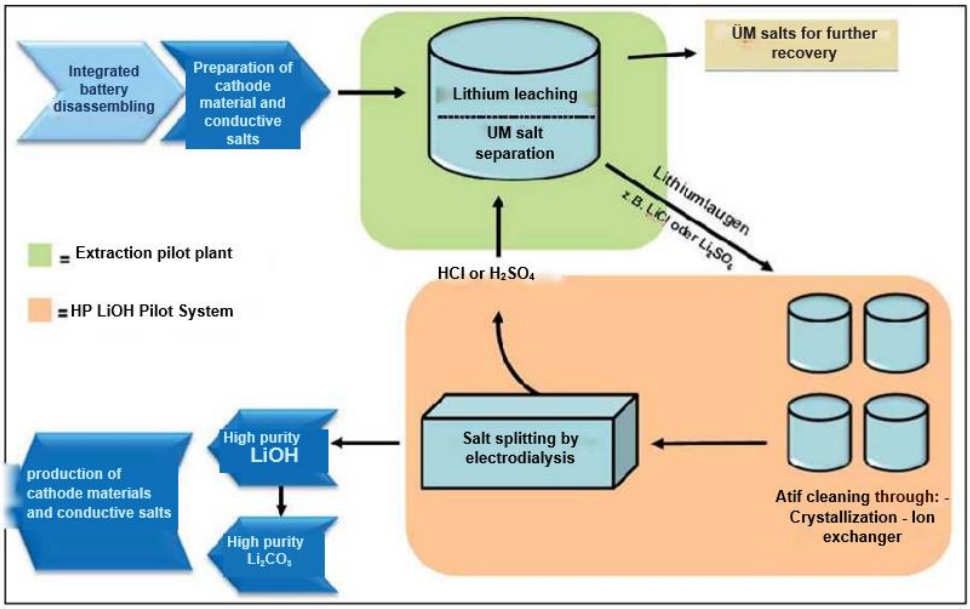


Figure B-30: Project scheme for hydrometallurgical battery material recycling

Figure 1: Project scheme for hydrometallurgical battery material recycling

The high-purity lithium raw material (primarily lithium hydroxide) produced in this way was tested for its suitability for use in the synthesis of lithium conductive salts and cathode materials. In particular, it can serve as a raw material for the production of the fluorine-free conductive salt or additive lithium bis-(oxalato)borate (LiBOB).

The laboratory processes developed and optimized for the extraction and separation of lithium and transition metal salts and for purification using ion exchangers and salt splitting using electrodialysis must be tested, verified and validated in a pilot plant. This is essential to demonstrate and validate the process capability of the recycling system in order to create the basis for the design of a large-scale plant.

Such a pilot plant for extraction was not available and was to be set up in parallel to the laboratory optimization processes in order to be able to test and validate the processes. This optimization is to be taken up and completed after the end of the project.

B.4.1 Laboratory work on hydrometallurgical extraction and purification processes

AP_CM_1.0 Preparatory work

As part of the preparation for the laboratory work to be performed, a comprehensive literature search was conducted, particularly with regard to the hydrometallurgical recycling of cathode materials of secondary lithium-ion batteries.

The general route repeatedly described in the literature deals with the digestion of lithium cobalt oxide using mineral acids such as nitric, sulphuric or hydrochloric acid under the accelerating effect of hydrogen peroxide at elevated temperature. Various processing steps are then performed to isolate the desired products.

Hydrometallurgical processing of cathode materials such as lithium manganese oxide, lithium cobalt manganese nickel oxide and lithium iron phosphate are hardly described in the literature.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The articles generally describe the recovery of the transition metals cobalt, nickel, manganese and copper. The recovery of lithium, which was the main focus of the project, is generally not described.

To make the content more easily accessible, summaries were written of particularly helpful literature and distributed to the employees involved.

Further research, which was necessary for the successful completion of the project, dealt with the topics of ion exchange, electrodialysis and filtration methodology. These were performed over the entire duration of the project.

For the extractions of the various cathode materials, different equipment was set up depending on the batch size and extraction conditions.

Round bottom flasks equipped with a stirrer, reflux condenser, heat source and, if necessary, dropping funnel, or small glass reactors were used for the laboratory-scale experiments.

A 30-liter double-jacketed reactor with thermostat was used for pilot-scale experiments.

A key purification step involved the separation of precipitates that occurred during the processing of the extraction solutions. For this purpose, two filtration options were tested: on the one hand, separation through porcelain filter nutsches, and on the other hand, filtration through pressure filters was performed in some tests.

A special glass apparatus was set up for crystallization. This made it possible to continuously feed the lithium salt solution, in which the dissolved salt to be crystallized was located, under reduced pressure and to crystallize the solid.

The main factors influencing the rate and equilibrium of chemical reactions are temperature, reaction time, type and concentration of the solvent and, if necessary, a reaction accelerator. The variation of these parameters has also been described in the literature. Another important factor is the cathode material/solvent ratio.

All of the above. parameters were taken into account when drawing up the test plans.

AP_CM_1.1 Digestion, dissolution and extraction processes for various electrode materials (fresh qualities)

As no materials from recycled batteries were available at the start of the project, pure materials used in lithium-ion batteries were used to develop the basic processes for the decomposition and extraction of the metal salt components from the liquid phase.

The use of such pure substances has the advantage of being able to develop and evaluate the desired processes without complications and in a time-efficient manner.

Lithium cobalt oxide and lithium nickel cobalt aluminum oxide could be purchased as fresh goods and were physically and chemically analyzed to the extent necessary for the extraction experiments.

The digestion of lithium cobalt oxide and, in this context, the variation of the various test parameters is described very well and in detail in the literature. For this reason, the main focus was on finding another viable route for this cathode material.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

No descriptions of digestions in basic media were found in the literature. Nevertheless, this option should also be tested as part of the project. Various concentrations of caustic soda were used for the reactions with and without the use of hydrogen peroxide as a reaction accelerator. With an extraction time of several hours, lithium was only detected in low concentrations in the extraction solution in all the tests performed; for this reason, the route was not pursued further.

In chemical industry processes, diluted acids repeatedly occur as by-products, which then either have to be disposed of or expensively reprocessed. The use of such diluted acids for extraction purposes would therefore be an elegant way of using them as a raw material. Therefore, extraction with diluted hydrochloric acid at room temperature was tested as a second variant. However, this variant for extracting lithium cobalt oxide also proved to be unusable. As a result, it was possible to extract larger, but not quantitative quantities of lithium with 3% hydrochloric acid at room temperature.

However, lithium nickel cobalt aluminum oxide could be digested to almost 100% under reductive, hydrochloric acid conditions on the basis of the literature data already available for lithium cobalt oxide.

Lithium manganese oxide and lithium iron phosphate could also be purchased fresh and were physically and chemically analyzed to the extent necessary for the extraction experiments.

In analogy to lithium cobalt oxide, tests were also performed for lithium manganese oxide with different concentrations of caustic soda with and without the use of hydrogen peroxide as a reaction accelerator or with 3% hydrochloric acid. In the case of lithium manganese oxide, lithium could also only be detected in low concentrations in the extraction solution after extraction in an alkaline medium. With 3% hydrochloric acid, larger, but not yet quantitative quantities of lithium could be extracted at room temperature.

Extraction using oxalic acid has been extensively tested for lithium manganese oxide in particular. As oxalate forms a poorly soluble solid with manganese(II), the reaction should only be performed using oxalic acid (without other chemicals).

The oxalic acid route proved to be a very elegant variant here, as oxalic acid acts as a reducing agent for the manganese(III) and manganese(IV) ions present in the cathode material and can therefore accelerate the decomposition of the cathode material. At the same time, the generated manganese(II) is precipitated as oxalate.

The reaction is exothermic, which also accelerated the reaction and made an additional heat source superfluous. The reaction conditions could be optimized in such a way that ultimately almost 100% of the lithium contained in the cathode material could be extracted.

Using lithium iron phosphate, the “classic” variant was tested using mineral acids (sulphuric and hydrochloric acid) with and without hydrogen peroxide.

Without the addition of hydrogen peroxide, the lithium yield was 30 - 40% in all the reactions performed. The extraction solution also contained undesirably high levels of iron and phosphate.

Under the effect of hydrogen peroxide, yields of > 95% lithium were obtained. In addition, the extraction solutions only contained small amounts of iron and phosphate. This is due to the fact that iron(II) from the cathode material reacts with hydrogen peroxide to form iron(III), which

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

reacts with dissolved phosphate at the resulting pH value to form sparingly soluble iron(III) phosphate.

In the manufacture of lithium-ion batteries, the cathode material is combined with the anode material (also in a discharged state and therefore lithium-free). During the first charge, lithium ions intercalate into the anode material. For this reason, lithiated anode material was not available for purchase as a fresh product. For the results of material mixtures of real systems, see AP_CM_1.3.

The circulation system was tested using the lithium manganese oxide/oxalic acid system. For this purpose, lithium manganese oxide was digested in a first extraction reaction and the extraction solution was isolated. In the second step, further lithium manganese oxide was added to this extraction solution and a further extraction was performed with the renewed addition of oxalic acid, so that it was finally possible to enrich lithium in the extraction solution.

In the digestions with mineral acids, all precipitates were washed with water to increase the yield of lithium. Here it is possible to combine the wash water with the actual extraction solution, which results in an overall decrease in concentration due to the increase in volume.

If this is to be avoided, it is possible to use the same wash water in several successive extractions to wash precipitates with adhering lithium salt until a sufficient concentration of lithium is present in the wash water for economical processing.

AP_CM_1.2 Separation/isolation of pure substances from AP_CM_1.1

(1st separation/cleaning step)

For all separations of transition metal salts from the extraction solutions, precipitation as a sparingly soluble metal salt was selected. Subsequently, adhering extraction solution was removed through several washing processes with subsequent filtrations in order to increase the lithium yield and thus obtain the transition metal salts free of lithium.

Various pH values were tested to optimize the precipitation reactions, and it was ultimately found that precipitation in the strongly alkaline range is more suitable for separation than precipitation in the weakly alkaline range.

At the same time, various filtrations were tested in order to achieve the most efficient product isolation possible. In this context, filtrations were tested at different pressures using various filter media with different pore sizes.

The isolated transition metal hydroxides were dried before further processing in order to be able to consistently balance the experiments.

To isolate transition metal sulphates, the next step was to investigate simple dissolution in sulphuric acid at various temperatures.

Surprisingly, the transition metal hydroxides investigated could hardly be dissolved even in a strongly acidic medium and therefore could not be converted into the corresponding transition metal sulphate.

In the end, conversion in acid with the addition of a reducing agent proved to be a successful route. Using this method, the necessary complete dissolution to acidic transition metal

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

sulphate solutions was finally achieved.

The method described above was subsequently used for the production of all other transition metal sulphates.

Two methods were tested for the pre-purification of the Li leaches and isolation of pure lithium compounds.

The first method is suitable for isolating lithium in the form of carbonate. This route is particularly suitable for isolating lithium from more heavily contaminated solutions where the use of an ion exchanger is not suitable. Here, the precipitation of lithium as lithium carbonate was performed by introducing carbon dioxide into the extraction solution as an example. After filtration of the sparingly soluble lithium carbonate, it was separated from the mother liquor in the heat (lithium carbonate is less soluble in a warm solution than in a cool one). By re-suspending the recovered salt in deionized water and reintroducing carbon dioxide, the lithium carbonate was returned to solution in the form of lithium hydrogen carbonate. Lithium carbonate was finally crystallized from this solution by driving off the dissolved carbon dioxide in the boiling heat and obtained in pure form.

After the first separation of the transition metals, the extraction solutions obtained generally contained such low transition metal concentrations that a depletion of residual quantities through ion exchangers was tested and successfully performed down to the single-digit ppm range.

In the special case of lithium iron phosphate, a separate pre-purification route had to be developed. If the solubility product is exceeded, dissolved phosphate can lead to undesired precipitation of lithium phosphate and thus to yield losses, which is why iron(III) sulfate was added to deplete phosphate and excess iron(III) was subsequently precipitated as hydroxide. This route allowed phosphate and iron(III) already contained in the water to be removed inexpensively in an extremely elegant way, without introducing other foreign substances/contaminants.

AP_CM_1.3 as 1.1, but materials from LithoRec or (if unavailable) mixtures of 1.1 and electrolyte residues

IPAT-TUBS provided the cathode materials lithium iron phosphate (formed) and lithium nickel manganese cobalt oxide (rejects and cyclized material) for the tests in this work package.

At IPAT-TUBS, the materials provided underwent various forms of processing, which, from Chemetall's point of view, can be roughly divided into the cutting/sieving/ultracentrifuge process, NMP extraction (N-methyl-2-pyrrolidone) and mechanical separation.

They all had the common goal of separating the cathode material from the aluminum drain foil as quantitatively as possible, with the highest possible yield of cathode material and the lowest possible contamination of aluminum.

The tests within this AP were based on the results of the tests on fresh materials from AP_CM_1.1. This showed that the hydrogen peroxide-accelerated reactions are preferable in terms of extraction yield and speed, which is why all reactions in this AP were performed with the addition of hydrogen peroxide in mineral acids.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The main result was that the test parameters from AP_CM_1.1 could be transferred to the materials provided by IPAT-TUBS.

In the case of lithium iron phosphate, it was noticeable that the lithium yield was slightly reduced compared to the fresh material and the content of iron and phosphate ions in the extraction solution was significantly increased.

This leads to a higher cleaning effort for the real materials.

The lithium nickel manganese cobalt oxide dissolved completely in all cases when suitable reaction conditions were selected, i.e. all valuable substances were analytically detected in the extraction solution. The mixture of binder and graphite was obtained as a residue.

To test the processability of mixtures of different cathode materials, lithium iron phosphate/lithium nickel manganese cobalt oxide mixtures were examined for their extraction behavior.

The mixtures could be extracted with the optimized reaction condition. In the 20:80 mixture, lithium was extracted almost quantitatively. As expected, significantly less lithium could be extracted with the 80:20 mixture.

To test the processability of mixtures of cathode material, anode and separator, the extraction behavior of lithium nickel manganese cobalt oxide/anode/separator mixtures was investigated. The weight ratio of cathode to anode/separator was about 1.5 to 1.

Lithium could be extracted almost quantitatively in all cases.

Pure anode material was provided by IPAT-TUBS towards the end of the project for analytical purposes, particularly with regard to the copper and lithium content. The material contained only marginal amounts of lithium (< 0.3%), which is as expected since it was material originating from a discharged cell. Aluminum was also only found in small quantities (< 0.1%), as the material was pre-sorted by hand. The copper content was determined to be 2.4%, which Chemetall considers to be a reasonable value for a separation process that has not yet been optimized.

Lithium iron phosphate contains traces of sulphide, which produce toxic, flammable hydrogen sulphide gas in reaction with acids. Within the scope of this AP, the simplest possible analytical method was therefore sought to detect traces of hydrogen sulphide gas in order to ensure health and environmental protection and to discuss any explosion protection issues that may arise.

To determine the concentration of the hydrogen sulfide odor, which is faintly perceptible during the addition of lithium iron phosphate to sulfuric acid, the hydrogen sulfide concentration was measured in several tests using a Dräger-Tube measuring system. The measurements were taken directly above the extraction suspension.

In all cases, discoloration of the initial area of the Dräger-Tube contents could only be guessed at. The concentrations were determined at ≤ 5 ppm.

Otherwise, the cathode materials provided did not contain any detectable levels of residual organics or impurities from conductive salts and electrolytes that would have required separate separation.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

AP_CM_1.4 Isolation of pure substances from AP_CM_1.3

The isolation of the transition metal salts and transition metal sulphate solutions was initially tested on a laboratory scale on various cathode materials and the samples were sent to HCST and the IPC-WWU for analytical purposes. Production was then performed on a pilot plant scale for HCST. New cathode material was produced from this material at HCST.

At the pH value of the theoretical precipitation range of aluminum, aluminum should first be precipitated as hydroxide and filtered off. However, it turned out that aluminum could not be quantitatively depleted.

The transition metal ions were then precipitated as hydroxides at an adjusted pH value, filtered off and washed.

The dried transition metal hydroxides were subsequently dissolved in sulphuric acid with the addition of hydrogen peroxide and the solution was sent to HCST for pilot plant tests.

In the course of the project, the real systems showed that the extraction solutions containing lithium could be depleted of all undesirable metal ions through hydroxide precipitation, filtration and washing processes very well and almost without loss (in relation to the lithium yield).

The solutions had such a low level of impurities that further direct purification could be performed using an ion exchanger.

The method developed for working up lithium salt solutions from lithium iron phosphate (described above) was successfully transferred to the real systems.

AP_CM_1.5 Purification (high purity) of Li-leach from AP_CM_1.2 and AP_CM_1.4 for electrodialysis

Generally, only high-purity salt solutions can be used as a starting material for electrodialysis processes. In particular, polyvalent cations must be depleted.

The tests using ion exchangers were essentially aimed at the three main aspects of cleaning effect, exchange capacity and regeneration.

For this purpose, ion exchanger systems consisting of specially manufactured heatable ion exchanger columns and dosing pumps were installed. The manufacturers of the ion exchange resins had no experience with the lithium salt solutions to be cleaned here, so that in this case it was not possible to fall back on existing specialist knowledge. It turned out that the experience gained from systems containing sodium could not be transferred to systems containing lithium. There were clear differences in the exchange capacity, among other things. This turned out to be significantly lower with the lithium system. In order to optimize capacity and cleaning effect, various ion exchange resins (basic, acidic and chelating) had to be tested at different test parameters (pH value, temperature and concentration of the solutions) to enable the most efficient work possible.

Ultimately, it was possible to produce high-purity lithium salt solutions using ion exchange, which were suitable for the EDBM system in terms of their impurity signature.

The lithium salt solutions must be completely free of solids before being fed into the electrodialysis, which can be achieved by membrane filtration, for example.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Microfiltration was used for fine filtration of the lithium salt solutions prior to EDBM. The general purpose of this pre-filtration is to extend the service life of the EDBM membranes, as premature blocking of the membranes by undissolved substances can be avoided. This means that longer service lives can be achieved.

Nanofiltration was also tested. For this purpose, a nanofiltration stand was set up and the general suitability of this method was tested for different parameters (e.g. pH value, concentration, pressure, impurity signature) for the purification of lithium salt solutions. As a result, this method proved to be suitable for cleaning. Depending on the parameters set, polyvalent ions, which would interfere with the EDBM, could be depleted very well.

In addition to the cleaning effect and the exchange capacity, the tests using ion exchangers were aimed at investigating regeneration. The ion exchange resin was flowed through with regeneration liquids of different temperatures. By analyzing and balancing the impurities in the wash water, it was possible to perform an optimization. According to the manufacturer, the resin is regenerated with acid and lye. In the tests, the resin was regenerated exclusively with different concentrations of hydrochloric acid and the influence on the capacity was investigated.

AP_CM_1.6 Optimization of electrodialysis

The aim of electrodialysis with bipolar membranes is to convert a salt (in this case lithium chloride or sulphate) into the corresponding acid (salt or sulphate) by means of an electric current. sulphuric acid) and lye (lithium hydroxide).

The electrodialysis tests on long-term behavior were initially performed with an external service provider, taking into account the known data. To this end, a detailed sampling plan was drawn up during the tests and the analytical methods for determining the concentration of the reactants and products were clarified.

It became apparent that building up in-house expertise in electrodialysis was essential and a laboratory EDBM system was procured. After familiarization with the topic, reference tests known from the literature were performed to determine the reproducibility of the data. In these experiments, different concentrations of sodium chloride solutions were electrodialyzed. It was found that the products from our cell had increased contamination levels of chloride and sodium ions.

The first EDBM tests were performed in a batch process. First of all, test parameters such as voltage, current, pressure and concentration were varied in order to achieve an optimum product yield in relation to the amount of charge used. The service life was determined for various parameters, taking into account the corresponding product quality. The focus was on the concentration of the lithium hydroxide and hydrochloric acid solution when performing the experiments.

Following all optimization tests and work, the EDBM plant was converted from batch operation to a continuously operating plant. Only through this conversion is it ultimately possible to simulate the conditions in the pilot plant on a laboratory scale and to test actual long-term behavior.

For this purpose, the system was equipped with specially manufactured feed and collection containers and expanded with additional pumps.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

In the next step, tests were performed to increase the product quality with regard to the purity of the lithium hydroxide.

Explanation:

The various solutions are pumped past the membrane surfaces through pumps within the membrane stack (parallel arrangement of individual membranes to increase the membrane surface area) through channels into the three different membrane chamber areas. Salt splitting takes place through the membranes using various ion exchange processes. Due to the method used, undesired permeation of ions through the membranes also occurs through the membrane surfaces and, within the membrane seals, undesired transitions of ions between the chambers, e.g. chloride or sulphate in the lithium hydroxide.

To reduce the above effects that lead to the described product contamination, the concentrations of the solutions in the different chambers were first varied in order to reduce unfavorable permeation effects as much as possible. No significant improvements were achieved here.

In the next approach, tests were performed in which the acid was diluted at regular intervals using deionized water in order to reduce permeation and, if necessary, exchange through leakages between the acid and the leaching chamber. In this case, there were also no improvements in product quality.

Finally, the purity was optimized by dismantling the diaphragm stack and replacing the diaphragm seals. Such a high reduction in the impurity signature was achieved that it was ultimately possible to obtain high-purity lithium hydroxide crystallizate from the lithium hydroxide solutions obtained here.

AP_CM_1.7 Purification of ÜM salts from AP_CM_1.2 and AP_CM_1.4 in battery quality or conversion into common battery raw materials

The transition metal salts should be purified in such a way that they can be used directly for the renewed production of battery materials for the next generation cycle.

Basic experiments on the conversion of transition metal hydroxides with inorganic acids (hydrochloric acid, sulphuric acid, nitric acid) into the corresponding salts were performed according to known synthesis instructions. This was followed by analytical tests of the salts for impurities and adaptation of the analysis methods.

Furthermore, centrifuge experiments were performed to dry the transition metal salts at different parameters. It was investigated which residual moisture contents can be achieved with corresponding amounts of energy. The transition metal salts were dried at different temperature programs and using vacuum. Finally, the test results were transferred to hygroscopic lithium salts. The following parameters were investigated: suspension density, centrifuge speed, duration of centrifugation and material feed.

Further purification options were tested. Various crystallization methods (cooling and evaporation crystallization) were used to improve the quality of the ÜM salts.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

B.4.2 Pilot plant for acid-based extractions and fluorine-free conductive salt production

Engineering/Assembly

Extensive approval documents were prepared in accordance with official or statutory requirements and administrative tasks were performed. These activities resulted, among other things, in the issuing of the approval notice in accordance with the BImSchG. Safety-relevant aspects were developed to the same extent and tested by independent institutes (e.g. TÜV Nord). Maintenance and repair work and possible by-products were also taken into account when assessing the hazards in accordance with GefStoffV. The risk assessment specifies the measures required to protect employees and third parties from hazards due to inhalation exposure and skin contact.

The results of a DFSS workshop together with the R&D department are directly relevant for the above activities. Design reviews of the virtual system (3D model) were performed with the operating personnel in order to ensure the best possible subsequent operation of the system.

In the process engineering work package, the process design was developed from the process concept and a detailed process flow diagram was created. The main focus was on the design of the solids conveying and dosing system, as the raw materials to be used had to be based on different grain sizes, specific densities and bulk densities. The units were designed and the process sequence was specified in detail with regard to the corresponding material requirements and reaction requirements.

The external detailed engineering and other engineering services were commissioned and completed on schedule. Chemetall's own engineering department supported and supervised the work.

The detailed engineering involved an in-depth process engineering design of the equipment, taking into account the information from the results of the installation planning, EMSR, steel scaffolding and platform construction, as well as the results of the tests performed at various manufacturers and institutions. The design drawings, R+I flow diagrams, layout plans and piping isometrics with support drawings resulting from the detailed engineering were created, checked and approved for installation. The bulk material was procured in accordance with the resulting mass extracts for piping, fittings and EI&C technology.

Due to the long delivery time, the first step was to complete detailed engineering for the dryer in advance, which led to the commissioning of the dryer design.

Important milestones in the detailed engineering were the completion of the layout planning and the steel construction master planning. In the layout planning, the system components were optimally arranged on the basis of process and safety specifications, but also taking into account maintenance and operating requirements.

The planning, design and calculation of steel structures for the equipment and piping was performed on the basis of static and dynamic load calculations.

Special support was a relatively costly element in this context.

In the first construction phase, the steel construction/raw construction including the necessary coatings, the package unit for solids handling and further bulk material tests, the operating equipment (crane system/lifting gear for material transport) and the vapor treatment were

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

ordered.

Pilot plant tests with solids were performed at the respective potential suppliers. The corrosion tests for conductive salt production were evaluated and materials for conversion work were ordered.

The inspection and production approval of the design drawings for the equipment and operating devices has been completed. To monitor production at the suppliers, various visits lasting several days were performed together with the technical purchasing department, e.g. 2 inspection/acceptance dates each for the reactor/mixer and solids handling. The solids handling system, the reactor/mixer, the vacuum systems and parts of the vapor treatment system were delivered and installed. The installation supervision was started at the same time as the installation of the equipment and piping, fittings and EI&C technology. Functional descriptions to define the control sequences and the specifications for the control cabinet planning were developed together with the suppliers and the EI&C department. Offers for the creation of the circuit diagrams and the switch cabinet construction were received.

Figure B-31: Main process components

A test run of the reactor/mixer was performed successfully. The connection of the heating/cooling system for the reactor/mixer has been completed. The expansion tank and the circulation pump of the heating/cooling system were adapted for the reactor/mixer.

Some of the existing pipework in the building had to be adapted so that the new equipment could be positioned and connected in accordance with the planning and manufacturer's requirements.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

It was ensured that production monitoring, pressure and leak testing and the acceptance of pipes subject to mandatory testing were performed in accordance with the requirements of the Pressure Equipment Directive and the Chemetall works standard. The insulation of the corresponding pipelines and system components has been completed.

The electrical connection as well as the inspection and functional test of the electrical, measuring and control equipment and the adjustment of this have been performed. The alarm, locking and switch-off points defined in the functional descriptions for determining the control sequences were checked. Special requirements of the extraction process with regard to explosion protection have been taken into account here. The programming and visualization of the control processes was completed.

Figure B-32: Solids handling

After mechanical completion, trial operation began in accordance with the commissioning schedule. Instruction and training for the operations manager, employees and technical staff was performed in parallel with the commissioning of the individual system components.

The first trial runs for the production of a conductive salt were successfully performed in the main components of the plant. During the trial operation, various changes were made to different parts of the pilot system (also due to complaints). These changes had to be initiated, monitored and documented. Finally, the ATEX certificate for the dryer/reactor was prepared and handed over by the notified body and the last system component (welding machine for the filling system) was delivered.

The suppliers' operating instructions have been checked and, in some cases, revised. In accordance with the technical specifications from the supplier documentation, a comprehensive operating manual was created and adapted to the special requirements during the trial operation. An operating manual has been created.

Furthermore, the necessary information for subsequent maintenance management was

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

compiled and entered into the SAP system to record the equipment and spare parts.

The §29a inspection of the system (conformity of the approved system with the system actually built) was successfully performed by TÜV-Nord. For this purpose, the actual structural condition of the plant was documented in advance by an as-built recording of the R+I flow diagrams and entered into the alarm and hazard prevention plans.

The official requirements and ancillary provisions from the approval notice were fulfilled.

In order to facilitate the implementation of the laboratory process in the pilot plant and to make it safer (e.g. due to possible contamination), further tests were commissioned in the area of extraction. The requirements for the pilot plant for the extraction tests with regard to explosion protection, the use of hazardous substances and plant safety were determined and evaluated on site and in meetings with the specialist and safety departments as well as with the production employees. The results were summarized in a report and implemented in the process design for the extraction tests.

Steel construction

The system to be built was installed in an existing building on the factory premises. This required special consideration, especially for the building and steel construction. First of all, platforms and stages that were no longer viable and other components that were no longer required had to be dismantled. The steel structures also included new internal staircases. A new external staircase was also installed for safety reasons. The outer gate had to be rebuilt and a splash guard curtain had to be moved.

An installation opening had to be created in the roof of the building so that the dryer could later be hooked into the steel frame.

The dismantling work was already completed in the first half of the year.

Construction plans for reactor and equipment platforms and specifications for the award of the shell construction and steel construction contracts were drawn up.

The steel construction drawings and static calculations were checked by the appointed test engineer and then handed over to the commissioned steel construction companies for the preparation of the production drawings. The steel construction, which was divided into 2 construction phases, was negotiated separately and awarded to 2 steel construction companies in accordance with the results of the negotiations. The first construction phase essentially involved simple components without interfaces to the equipment, such as stairs and building openings, gates, etc. In the second construction phase, with much more complex components, steel platforms were constructed and designed for the apparatus. On the one hand, the operating weights for different cathode materials and, on the other, numerous process/safety-related specifications as well as the optimum maintenance and operation of the equipment had to be taken into account.

During the erection of the steel platforms and stairs, health and safety coordination was performed by an appointed coordinator, who also supervised the installation. Deadline and cost tracking as well as regular safety inspections were performed on an ongoing basis.

Various acceptance tests were performed (inspections by structural engineers, TÜV inspections of systems for water-polluting substances, expert inspections of hoists/cranes).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Maintenance platforms with ladders were planned for the dust extraction filters and the new expansion tank for the heating/cooling system in accordance with the design review. The necessary steel construction drawings and static calculations were prepared.

The final acceptance certificate is available. Necessary changes were made during the trial operation.

Further activities after project completion

Procurement of cathode material and chemicals. Final review of the process design and the safety concept for the materials provided. Subsequent information of the approval authority about the planned pilot tests. Preparation of the detailed test plan. Start of pilot tests and evaluations.

B.4.3 Pilot plant for purification using ion exchangers and salt splitting using electrodialysis

In principle, both membrane electrolysis (EMP) and electrodialysis with a bipolar membrane (EDBM) can be used to purify brines containing lithium. At the beginning of the project, it was assumed that the EDBM would be used for Li2SO4 and the EMP for LiCl.

Since no recycled material from cathode material containing lithium was available, the necessary preliminary tests and characterization of the process steps had to be performed with a synthetic substitute brine (“master brine”). As part of a “Design for Six Sigma Workshop”, a preliminary product specification for LiOH was developed, which enabled a comparison of the impurity pattern of the replacement system with the brines from the recycling process used later.

The available state of knowledge regarding the electrochemical production of LiOH was examined with regard to its use in this project. This has shown that the electrochemical conversion of lithium-containing brines into LiOH requires targeted purification of these brines because the permselectivity of the available membrane processes is not sufficient.

For the separation of divalent cationic impurities, it was decided to use an appropriate ion exchange system. The design data for the ion exchange system with regard to flow rate and pH value were determined and verified in-house.

A membrane filtration process was investigated to reduce anionic impurities. The membrane filtration was tested in cooperation with an external service provider.

Previous studies have already demonstrated the suitability of electrochemical processes for converting lithium salts into LiOH. A basic process model for membrane electrolysis (EMP) was available. However, the initial examination of the data revealed the need to determine further parameters in order to ensure the safe operation of the system in particular.

To ensure the safe operation of the membrane electrolysis (EMP), a test plan was drawn up on the basis of a “Design of Experiments” and worked through with an external research service provider. One of the subjects of the investigation was the behavior of the safety-critical gases chlorine and hydrogen with regard to their solubility in our material system. The process management and monitoring on the product side was adapted on this basis. Furthermore, the informative value of the process model for the behavior as a function of pH value and current

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

strength during membrane electrolysis was confirmed. It served as the basis for the process engineering design of the pilot plant.

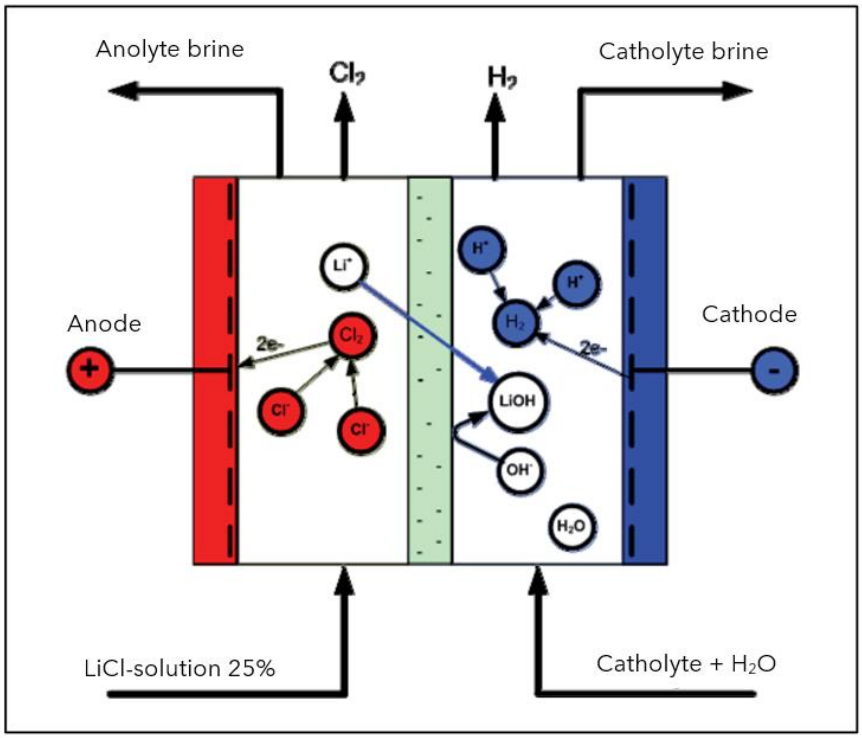


Figure B-33: Functionality of an electrolysis with monopolar membrane

At the same time, preliminary tests were performed with the synthetic substitute brine ("Masterbrine") using an electrodialysis process (EDBM). In this method, the dissociation of the water is enhanced by a bipolar membrane. The lithium-containing brine is converted into the corresponding inorganic acids and alkalis with the aid of anion- or cation-selective membranes. In particular, the formation of gaseous chlorine is avoided.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

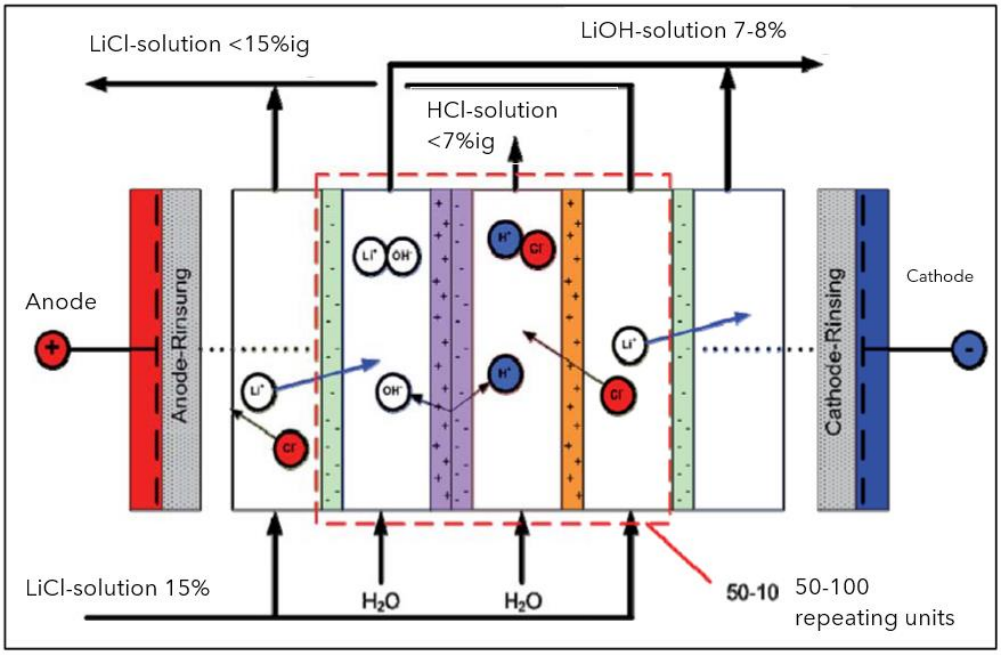


Figure B-34: Functionality of electrodialysis with bipolar membrane

After the R&D work was completed together with external research institutions, the process layout (process engineering planning) for these two technologies was driven forward and brought to completion. Technical negotiations were then commenced with two suppliers. At the same time, quotation specifications for the gas and liquid treatment systems were fully developed, which, like the electrodialysis systems, have a long delivery time so that they can be ordered in good time. As part of this, an initial SHE (Safety-Health-Environment) review has already been performed to assess the impact of the project on the environment.

The investigations into electrochemical salt splitting have shown the following:

- The EDBM is suitable for the production of lithium hydroxide from lithium sulphate as well as from lithium chloride
- The comparison between EMP and EDBM for LiCl showed approximately the same product qualities, i.e. Chloride content in the LiOH solution
- The experiments with the EDBM could be performed with larger membrane surfaces due to the lower equipment requirements (no treatment of gaseous by-products), so that a transfer to pilot scale is more feasible than with the EMP
- An endurance test (1,000 h) with LiCl solution was successfully performed for the EDBM
- In the development cooperation with the two leading European manufacturers for EMP, it was not possible to find a common basis for protecting the know-how acquired by Chemetall for the electrochemical process step, as the systems are only sold with a license model
- Systems for EDBM are sold without a license model, as is usual for equipment for the chemical industry

Based on these results, it made sense to perform the electrochemical salt splitting for both the

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

LiCl solution and the Li2SO4 solution using an EDBM.

A comparison of the two concepts shows the differences between the improved concept:

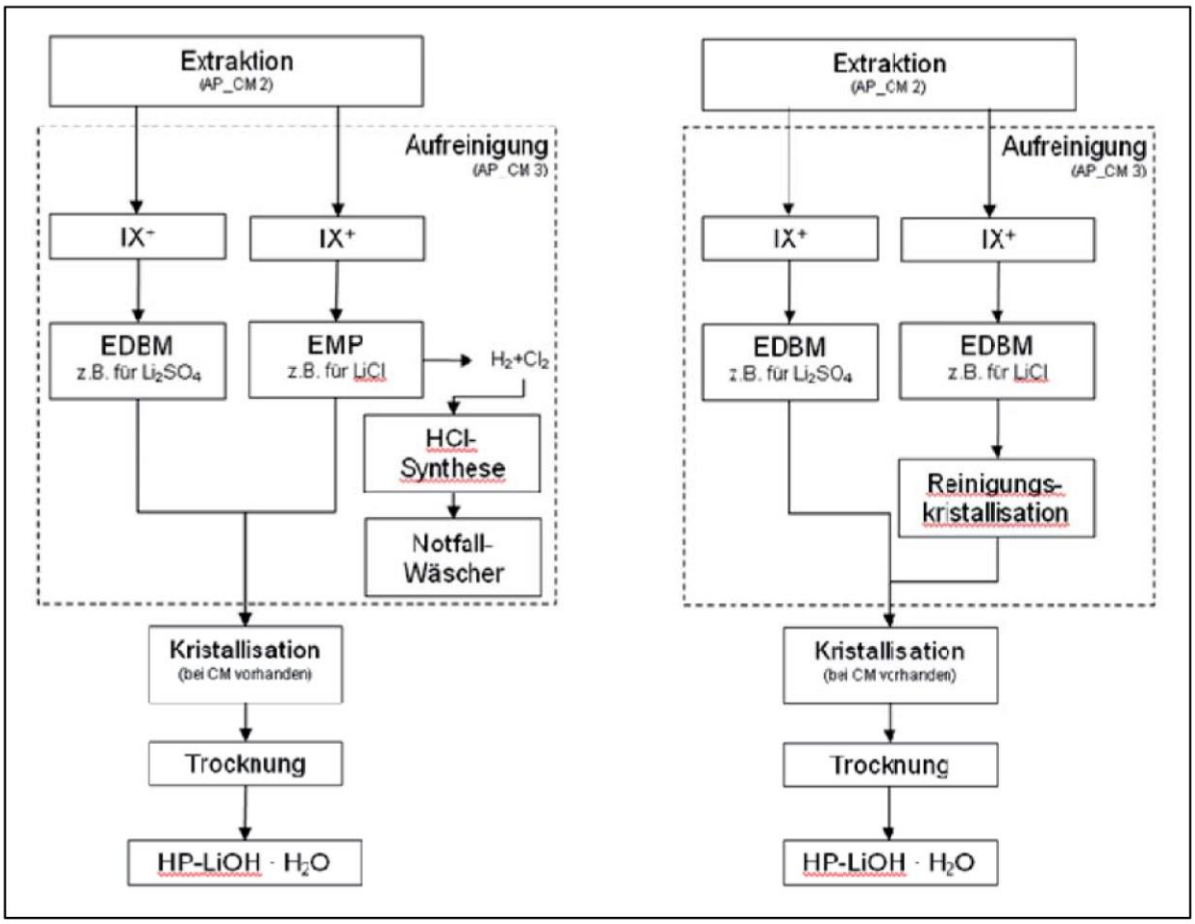


Figure B-35: Original and improved process concept

Image key:

German	English
Extraktion	Extraction
Aufreinigung	Purification
Kristallisation (bei CM vorhanden)	Crystallization (present in CM)
z.B für	E.g for
Trocknung	Drying

In the improved concept, the EMP was replaced by an EDBM. As no chlorine gas is released in this process, HCl synthesis and the emergency scrubber system are not required. However, cleaning crystallization is also required.

The emergency scrubber system required with the original concept consisted of the components scrubber column, Venturi scrubber, cooler, pumps and tank. The omitted HCl synthesis included the chlorine gas cooler, condensate filter, absorption tank, filter, tank and the actual hydrogen chloride combustion.

The purification crystallization in the improved concept is designed as a forced circulation

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

evaporator with an external heat exchanger for the LiOH solution. The crystallization process is performed under negative pressure. The negative pressure in the crystallization apparatus is set with a condenser and a vacuum pump for the non-condensable gases. The crystallizate is separated from the mother liquor using a centrifuge and washed with deionized water on the centrifuge. The solid is then dissolved in deionized water (8% LiOH solution) and added to the existing crystallization.

In summary, the advantages of the modified concept were the reduction of the scale-up risk, the avoidance of the treatment of hazardous gases (Cl_2 and H_2) and the assurance of know-how protection. In addition, it was ensured that the planned costs and completion date would be met. The modified process concept is used to produce a generally usable high-purity lithium hydroxide.

A supplier was selected that has many years of experience in the manufacture of membranes as well as in the design and manufacture of EDBM systems.

Appropriate tests were performed at this supplier in order to adapt the EDBM technology to the lithium-containing solutions. Membranes could be supplied for both the LiCl solutions and the Li2SO4 solutions. This made it possible to obtain a complete solution for the EDBM plant section including piping, circulation tank, measuring and control equipment as well as the associated engineering and commissioning.

By supplying both EDBM cells from one manufacturer, the time lost due to refocusing could be eliminated and the budget adhered to.

After the decision was made to pursue the modified process variant, the procedural work was started immediately in order to finalize the tenders as quickly as possible. In December 2010, the contracts for the main items electrodialysis modules and purification crystallization were awarded.

The height of the purification crystallization plant (18 m) and the general space requirements of all planned plant components necessitated an extension to an existing building, which was implemented outside of the funding project.

The process for pretreating the raw saline solution and processing the by-products was developed in basic engineering. In addition, the in-process analysis was developed together with the quality laboratory in Langelsheim. The materials and components for the EI&C technology were specified with the suppliers. The installation planning for the large appliances was performed in cooperation with the suppliers. The pilot plant was assessed by the trade supervisory authority as a test plant and therefore did not require a permit under the BImSchG.

The detail engineering included, among other things, the planning of the process engineering process developed in basic engineering. Contract negotiations were conducted with the suppliers of ion exchangers, tanks, pumps and other equipment.

The pipeline routing was planned for the main process and the infrastructure lines were planned. The safety analysis was performed using failure effect analyses for the individual system components. The installation work was planned and awarded. To ensure the smooth running of the construction site, preparations were made to integrate the assembly activities into everyday production and the infrastructure at the Langelsheim site.

Assembly began during the detail engineering phase. Three additional tanks with agitators

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

were installed in the tank farm for the storage of starting, intermediate and product solutions. For integration into the plant network, the supply and discharge pipes from the extraction plant and to the crystallization plant were installed in the lithium special salts production plant.

The eight racks for the electrodialysis modules and the associated rectifiers were delivered in May 2011. Due to their size, these system components were brought onto the top platform of the building through a roof hatch with the help of a crane. Furthermore, filters, heat exchangers and the stripping columns were positioned on the new intermediate platform and the containers were set up on the lower level.

At the beginning of June, work began on installing the piping for the electrodialysis system. After completion, the EDBM system was subjected to a pressure test. This was followed by the EMSR installation of the EDBM. The EDBM system was supplied and installed as a complete system.

Figure B-36: EDBM system

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure B-37: Saline solution treatment

Extensive safety analyses were performed with a focus on the operating equipment system. The plant personnel were trained internally.

The crystallization apparatus (evaporator, heating chamber and circulation pipe) was installed and assembled in the newly erected steel structure. The piping for crystallization, Brine processing and the supply of operating materials was installed. This was followed by the EMSR assembly crystallization, Brine preparation and operating equipment.

The ion exchange system must be operated at defined concentrations, pH values and temperatures. The crude salt solutions from the extraction step (pre-process) show a relatively large fluctuation range for these parameters. Therefore, process tanks for concentration adjustment and pH value adjustment and a flow heater for setting the temperature level were provided in the so-called Brine treatment. The ion exchanger was supplied as a complete system. The installation was performed in August.

The process parameters for operating the ion exchanger were developed in our laboratory and will be validated and optimized in the pilot phase after the end of the project. After the ion exchanger, the solution is stored temporarily until it is released. In our quality laboratory in Langelsheim, an existing analysis method (ICP) was optimized with regard to trace analysis. A new semi-automatic sampling procedure was designed and implemented for the collection of representative samples, which enables particularly safe and contamination-free sample handling. The released raw saline solution is then transferred to a storage tank and made available to the EDBM process in a circulation line.

The installed EI&C technology was subjected to an extensive functional test. The breathing system (inertization) was installed. The entire piping system was subjected to pressure tests. A safety analysis was performed in preparation for commissioning. External training was

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

provided for plant personnel. The installation of the system was fully completed and the automated control of the system was tested with a water ride. In a first operating test, the product LiOH and hydrochloric acid was produced from a LiCl solution. During the pilot operation phase after the end of the project, plant parameters are optimized with regard to process stability and product quality.

In total, around 60 individual units of equipment and equipment groups with a total of 2.3 km of piping were installed as part of this project. For process control, 380 measuring and control devices with a total of 15 km of cable routes were installed.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

C Development of manufacturing processes for “recycling batteries”

Thorough quality control and characterization of the raw materials for active material synthesis is of central importance. On the one hand, these are the end products of the metallurgical recovery of lithium and transition metal salts (**AP B.4,** CM), on the other hand, they are the starting materials for the synthesis of active materials (SC, HCST in **AP C.2**). The output and input control should ensure that only raw materials with sufficient potential are fed into the active material synthesis. By characterizing the raw materials, a sound understanding of the relationship between the recycling process (**AP B.3**), raw material quality and hydrometallurgical recovery (**AP B.4**) is obtained. HCST requires at least 200 liters of a 10% transition metal salt solution to operate the smallest reactor for the production of the NMC active material. The quantities of formed and cyclized materials required for this were not available in the project. Furthermore, these could not have been processed by the other project partners as part of the project and the corresponding preliminary stages could not have been provided. The partners therefore agreed to test samples with targeted contamination or simulated solutions on a laboratory scale. As all partners have experience in the area of up-scaling, this alternative approach was not expected to have any negative impact on the overall result. The fabrics go through the process shown below and are thus sufficiently tested for quality.

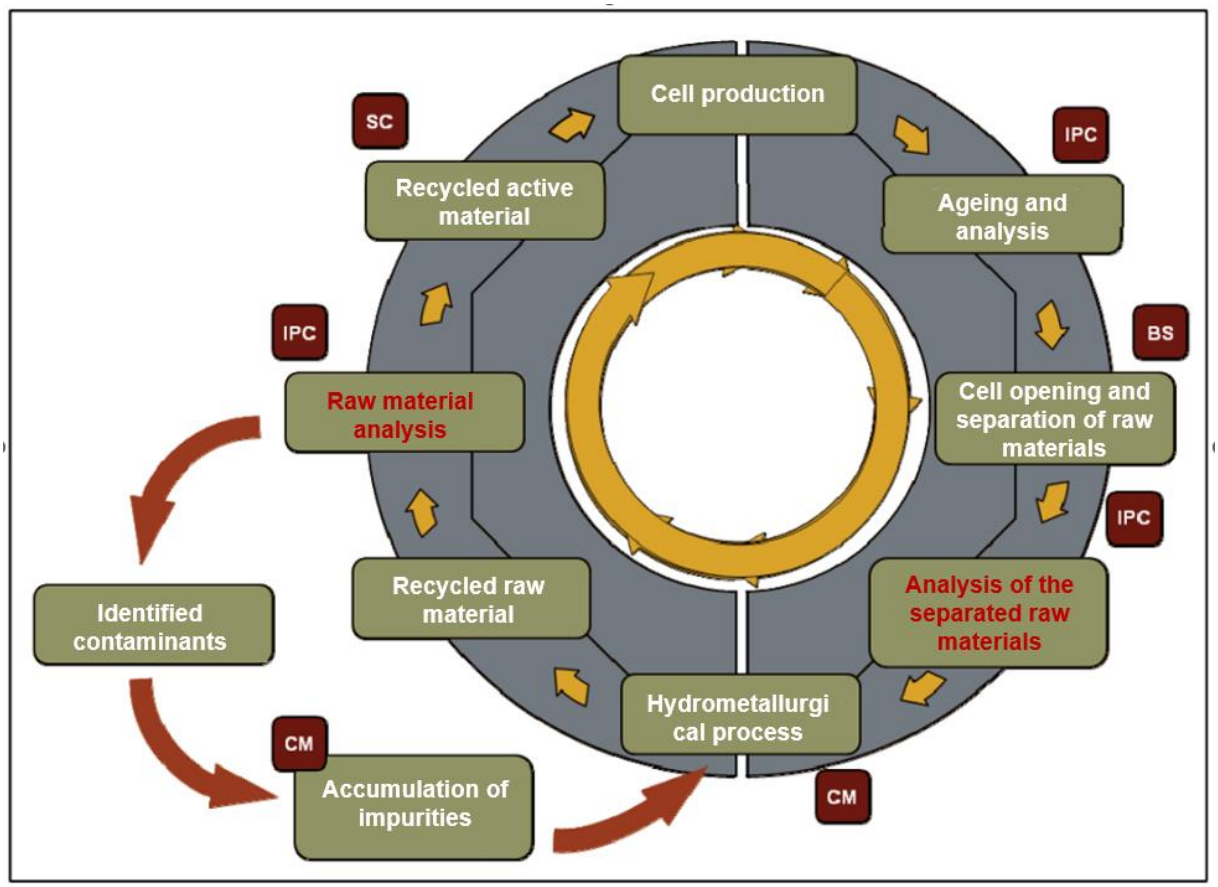


Figure C-1: Changed recycling cycle

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

C.1 Characterization of the recycled raw materials

In consultation with CM, HCST has drawn up a specification for recycled transition metals/transition metal salt solutions and recycled lithium base materials (LiOH, Li_2CO_3). It will be shown later (**AS C.2.3**) that a costly separation of all minor components may not be absolutely necessary and that the separation of interfering cations (especially Al) from the recycling solutions can be a cost-effective option.

C.1.1 Creation of a raw material specification for the recycled lithium raw materials by the active material manufacturers

At the start of the project, compliance with the above specification was seen as an essential precondition for reproducible representation of the active materials. The results of the internal project agreements on the specifications of the transition metal solutions are shown in Table C-1. Values in bold indicate that compliance with the specifications would probably be difficult to achieve or monitor. The concentration of all non-listed metals should be less than 5 ppm. In addition, the solutions should be free of crystalline components (cf. components insoluble in H_2O).

Table C-1: Specifications of the NiSO4/CoSO4 solutions for LNCAO (left) and LNMCO (right)

Component	Salary (LNCAO)	content (LNMCO)
Nickel (Ni)	15.0 ± 0.5 g/l	34.01 ± 0.5 g/l
Cobalt (Co)	85.0 ± 0.5 g/l	34.15 ± 0.5 g/l
Manganese (Mn) 1)	**max. 20 ppm**	31.83 ± 0.5 g/l
Copper (Cu)	max. 10 ppm	max. 10 ppm
Aluminum (Al)	max. 20 ppm	max. 20 ppm
Iron (Fe)	max. 15 ppm	max. 15 ppm
Silicon (Si)	max. 10 ppm	max. 10 ppm
Titanium (Ti)	max. 10 ppm	max. 10 ppm
Zirconium (Zr)	max. 10 ppm	max. 10 ppm
Zinc (Zn)	max. 10 ppm	max. 10 ppm
Phosphorus(P)	max. 10 ppm	max. 10 ppm
Fluorine (F)	max. 10 ppm	max. 10 ppm
Chlorine (Cl)	max. 1,000 ppm	max. 1,000 ppm
Carbon (C) 2)	**max. 20 ppm**	**max. 20 ppm**
Components insoluble in H_2O	**max. 25 ppm**	**max. 25 ppm**
pH (min. - max.)	2 - 6	2 - 6

In addition to the specifications for the transition metal solutions, specifications were also

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

drawn up for the Li compounds to be used. The results are shown in Table C-2 and Table C-3.

Table C-2: Specifications for LiOH*H2O

	HCST	After consultation with CM	SC
LiOH	min. 56.5%		55.1 - 56.1%
Na + K	max. 0.3%		max. 0.01%
Fe_2O_3	max. 0.001%		max. 0.01%
Mg	max. 0.01%	0.2%	max. 0.003%
Ca	max. 0.016%	0.2%	max. 0.003%
CO_2	max. 0.35%		max. 0.35%
Cl	max. 0.05%		max. 0.003%
Components insoluble in H_2O	max. 0.1%		max. 0.01%
	HCST	**After consultation with CM**	**SC**
Li_2CO_3	min. 99%		min. 99.9%
Na	**max. 0.1%**	**Na + K = 0.2%**	max. 0.002%
K	**max. 0.001%**		max. 0.002%
Mg	**max. 0.01%**	**0.2%**	max. 0.003%
Ca	**max. 0.016%**	**0.2%**	max. 0.003%
Fe_2O_3	max. 0.003%		max. 0.003%
Cl	**max. 0.015%**	**0.04%**	max. 0.002%

- Metals not listed < 5 ppm

Table C-3: Specifications for Li_2CO_3

	HCST	After consultation with CM	SC
Li_2CO_3	min. 99%		min. 99.9%
Na	**max. 0.1%**	**Na + K = 0.2%**	max. 0.002%
K	**max. 0.001%**		max. 0.002%
Mg	**max. 0.01%**	**0.2%**	max. 0.003%
Ca	**max. 0.016%**	**0.2%**	max. 0.003%
Fe_2O_3	max. 0.003%		max. 0.003%

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Cl	**max. 0.015%**	**0.04%**	max. 0.002%

In summary, if the defined specifications are adhered to, it should be possible to synthesize active materials from recycled precursors without compromise.

As chloride and sulphate impurities in the active materials require particular attention, SC as the active material manufacturer has specified maximum quantities of chloride and sulphate for lithium hydroxide (see Table C-4).

Table C-4: Raw material specification of lithium hydroxide monohydrate

	Min.	Type.	Max.
Li content (%)	15.8		
Assay ($LiOH.H_2O$) (%)	55.5	56.0	56.5
Chlorides (ppm)			50
Sulfates (ppm)			200

C.1.2 Evaluation of recycled lithium and transition metal salts in comparison with commercial and recycled primary raw materials

The recycled materials underwent various characterization and evaluation stages. This was necessary in order to achieve a balance between quality, efficiency and cost-effectiveness for the recycling process. To this end, all partners involved had to perform a repeated (iterative) analysis and evaluation of the recyclable materials obtained in the context of the various upstream separation and purification steps as well as the possible downstream use. As part of this work package, SC was provided with several lithium hydroxide monohydrate samples specifically contaminated with lithium sulfate (range 20- 1000 ppm sulfate) and a larger amount of lithium hydroxide monohydrate (battery grade) from CM. The tolerable sulphate contents in the lithium hydroxide were to be determined in the form of simulation tests. For HCST, extractions of lithium nickel manganese cobalt oxide (cyclized) were performed in the CM laboratory on a pilot plant scale. The transition metal sulphate solution obtained from these conversions and subsequent processing steps was sent to HCST to check the usability of the material for the production of new cathode material.

One (V21) was active material from formed cells, the second (V5-Z) was cyclized material. The powders and solutions supplied were subjected to elemental analysis by the partners.

Table C-5: Concentrations and pH values of the solutions of LNCMO V21 vs. LNCMO V5-Z

Test characteristic	LNMCO V21	LNMCO V5-Z	LNMCO V5-Z * 1.345 [1)]
pH value at 20°C	4.0	2.8	
Li	approx, 0.560 g/l	approx, 4.8 g/l	6.46 g/l
Ni	39 g/l	29 g/l	39 g/l
Co	38 g/l	28 g/l	37.7 g/l

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Mn	32 g/l	25 g/l	33.6 g/l
Al	0.238 g/l	1.1 g/l	1.48 g/l
Cu	<10 mg/l	768 mg/l	1.033 mg/l
Fe	<10 mg/l	22 mg/l	29.6 mg/l
Mg	approx. 14 mg/l	approx. 25 mg/l	33.6 mg/l
Si	approx. 14 mg/l	approx. 85 mg/l	114 mg/l
SO_4	180 g/l	180 g/l	242 g/l

[1)] A factor of 1.34 was chosen empirically in order to be able to directly compare the composition of the formed (LNMCO V21) and the cyclized (LNMCO V5-Z) active material (assumption: same Ni- concentration in the reaction solution).

However, the deviation in the concentration of the transition metal cations relevant for the synthesis of the active materials was well below 10% for both materials.

Finally, it should be noted that the compositions of the recycled solutions in no way correspond to the specifications defined in **AS C.1.1.** In order to achieve the defined specifications, it is essential to implement cost-intensive processing steps and to completely isolate the source materials. However, in order to operate as cost-effectively and efficiently as possible, further systematic studies must be performed to determine the extent to which higher concentrations of impurities can be accepted without negatively affecting the performance of the active materials.

C.1.3 Comprehensive analysis of chemical and physical material parameters and assessment of potential reuse

The aim of this overarching view of CM was to evaluate the reuse of materials and thus the quality, efficiency and cost-effectiveness of the successive recycling processes.

Therefore, chemical and physical material properties of differently produced transition metal salts were analyzed. The bulk density, particle size distribution and surface properties of the materials were examined in more detail. These parameters have an influence on the technical processing of the materials. Furthermore, a physico-chemical method was developed for the in-house characterization of active material/raw materials. Conventional electrochemical measurement methods were adapted to the special requirements and needs.

C.1.4 Evaluation of possible uses for different qualities of recovered raw materials

Lithium salts are used in many different applications. Lithium carbonate, which can be produced by reacting lithium hydroxide with CO_2, is used in the glass industry, for example. Here, for example, it is used as a superplasticizer in glass production and can replace boron

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

and fluorine in glass production, thereby reducing air pollution. In enamel applications, glass coatings are applied to metal at high temperatures to increase corrosion resistance. The very thin layer also increases the impact resistance (enamel is brittle). For glass ceramics (e.g. hobs), the coefficient of thermal expansion is reduced to almost zero so that no thermally induced stress cracks occur. With large telescope mirrors, thermal non-expansion enables optical freedom from error.

Further applications can be found in aluminum electrolysis. The main advantages here are a reduction in energy consumption and the release of hydrogen fluoride. In the construction industry, lithium carbonate is used for fast-binding Al_2O_3 cements. The Li cation from Li_2CO_3 binds a large number of water molecules, resulting in the precipitation of a LiAl hydrate, which functions as a nucleation substrate. Lithium hydroxide is mainly used in the lubricating grease industry. Advantages are a high dropping point, no leakage, excellent water resistance (lubricant is not washed out), a wide temperature range and a long service life. A very interesting application can be found in CO_2 absorption in submarines, rescue capsules, etc. In addition, there are a large number of other lithium salts in various applications (e.g. for catalysis, welding and soldering fusion agents, moisture control, air separation by adsorption, vulcanization baths for complicated profiles (car window rubbers, windscreen wipers), heat transfer medium, etc.).

In order to assess the suitability of the recycled lithium salts for non-battery applications, the certificates of analysis of the recycled salts were first evaluated. In each case, the requirements for the lithium salts in the various fields of application (specifications) were compared with the analysis results. One major challenge was that the individual customer specifications differed considerably in some cases. If deviations occurred here, optimization options were examined.

C.2 Synthesis and characterization of recycled active materials

The objective was the synthesis and complete characterization (chemical, structural, electrochemical) of LNCMO materials from recycled cells. For this purpose, a sample was synthesized from a formed material (LNCMO V21) and a cyclized material (V5-Z) and compared with a reference material from commercial precursors presented under the same conditions. Due to small sample quantities, no original solutions were used, but reaction solutions were simulated on the basis of elementary analytical data.

The $LiFePO_4$ samples produced with contaminated LiOH raw materials on both laboratory and pilot plant scale showed no significant deviations in the elemental analysis. In particular, the S content in the final product did not increase, and the specific capacity of the samples obtained remained within the expected, specified range.

C.2.1 Synthesis of active materials from recycled raw materials

The synthesis of LNCMO active materials from recycled raw materials was discussed in **AS C.2.1**. In addition to the presentation of LNMCO V21 obtained from formed cells and LNMCO V5-Z obtained from cyclized cells, an LNCMO reference material was synthesized promptly from commercial, high-purity precursors under identical conditions for direct comparison.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Table C-6 lists the raw materials used (all sulfates, silicon was added to the reaction mixture as sodium silicate, Na_2SiO_3) and the quantities of substances calculated from the analyses.

Table C-6: Simulation of the solutions (metal salt in g/l solution)

	M_{Metal} [g/mol]	M_{Salt} [g/mol]	LNCMO V21 (metal) [g/l]	LNCMO V5- Z (metal) [g/l]	LNCMO V21 (metal salt) [mol/l]	LNCMO V5-Z (metal salt) [mol/l]
Li_2SO_4	13.88 [1)]	109.94	0.56	4.80	0.04034582	0.34582133
$NiSO_4$	58.70	154.76	39.00	29.00	0.66439523	0.49403748
$CoSO_4$	58.93	154.99	38.00	28.00	0.64483257	0.47514001
$MnSO_4$	54.94	151.00	32.00	25.00	0.58245358	0.45504186
$Al_2(SO_4)_3$	53.96 [2)]	342.14	0.24	1.10	0.00441067	0.02038547
$CuSO_4$	63.55	159.61	0.01	0.77	0.00015736	0.01208497
$FeSO_4$	55.85	151.91	0.01	0.02	0.00017905	0.00039391
$MgSO_4$	24.30	120.37	0.01	0.03	0.00057613	0.00102881
Si	28.08	--	0.01	0.09		

[1)] Molar mass related to Li_2; [2)] Molar mass related to Al_2

Table C-7 lists the quantities of substances used in the synthesis. These are shown in Table C-6, taking into account equimolar quantities of the transition metal sulphates (so-called one-third mix). The concentrations of the "impurities"$Al_2(SO_4)_3$, $CuSO_4$, $FeSO_4$, Li_2SO_4, $MgSO_4$ and Na_2SiO_3 remained unaffected by this adjustment and were set according to the analyzed values.

Table C-7: Simulation of the solutions for the exact one-third mix with Ni:Co:Mn = 1:1:1

	LNCMO V21 (metal salt) [mol/l]	LNCMO V5-Z (metal salt) [mol/l]	LNCMO V21 (metal salt) [g/l]	LNCMO V5-Z (metal salt) [g/l]
Li_2SO_4	0.04034582	0.34582133	4.4355389	38.0189049
$NiSO_4$	0.66439523	0.49403748	102.821806	76.467121
$CoSO_4$	0.66439523	0.49403748	102.974617	76.5708688
$MnSO_4$	0.66439523	0.49403748	100.317036	74.5947189
$Al_2(SO_4)_3$	0.00441067	0.02038547	1.5090682	6.97468495
$CuSO_4$	0.00015736	0.01208497	0.02511566	1.92888245
$FeSO_4$	0.00017905	0.00039391	0.02719964	0.05983921
$MgSO_4$	0.00057613	0.00102881	0.06934897	0.12383745

The active materials are presented in two stages. First, a precursor is synthesized hydrometallurgically, which already has the typical morphology and Ni:Co:Mn ratio of the cathode material. Following the addition of the lithium component, calcination takes place,

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

which results in dehydration of the precursor, oxidation of the transition metal ions, decarbonization of the lithium carbonate and intercalation of the lithium into the transition metal oxide lattice. Finally, the active material is deagglomerated and conditioned by jet milling. Both the precursors and the milled active materials were characterized in detail structurally and electrochemically. The results of these investigations can be found in **AS C.2.3**.

C.2.2 Production of conducting salts from laboratory recycled materials and comparison with commercial conducting salts

Analytical methods for determining the purity of LiBOB were performed as part of the *LithoRec* project. Water and boric acids were identified and defined as important impurity components. The preferred method is based on 1H-NMR measurements with an internal standard (EC). Several batches of laboratory-produced products were tested. Contamination with ammonium was identified, the cause of which is still being clarified.

Long-term NMR tests were also performed and evaluated. In addition to NMR investigations, various methods of water analysis (Karl Fischer methods) were used. An experimental program for the production of LiBOB from LiOH, boric acid and oxalic acid was performed. The influence of different LiOH qualities produced by electrodialysis on the quality of the conducting salt was investigated.

In long-term storage tests, a correlation between boric acid and water content was established.

LiBOB from lithium hydroxide and lithium carbonate mixtures to optimize quality were produced in the laboratory. High-purity Li_2CO_3 was mixed with slightly contaminated LiOH from electrodialysis and the influence on the quality was investigated.

C.2.3 Characterization of active materials - product output control

The synthesis of the precursor already showed that the two recycling solutions of LNCMO V21 and LNCMO V5-Z behave very differently in the precipitation process.

In addition, the different concentrations of impurities in the reaction mixture significantly influenced the morphology of the particles. The SEM images shown in Figure C-2 show that the powder formed from the molded material is all comparatively dense spherical particles. In contrast, the SEM images of the V5-Z precursor show particles with a high surface roughness. The optical determination of the particle size distribution (Mastersizer) confirms these findings. The D50 values of the LNCMO V21 are 8.7 - 9.0 µm, those of the LNCMO V5-Z are 4.6 - 6.8 µm. Although larger particles are present on average in the first case and these appear denser in the SEM images, their specific surface area (Tristar) of 11.5 - 12.2 m^2 /g is significantly larger than that of the LNCMO V5-Z, which is 7.2 - 8.1 m^2 /g. The appearance of the precursor from LNCMO V21 thus largely corresponds to that of the reference materials from commercial precursors (not shown).

The influence of the impurities on the morphology of the LNCMO materials is clearly evident after calcination. Figure C-3 compares the SEM images of the reference material, the LNCMO

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

V21 and the LNCMO V5-Z. The reference material and V21 are produced in the form of spherical particles after annealing. These are available in completely deagglomerated form. In contrast, the overview image of the LNCMO V5-Z shows that primarily regular, strongly intergrown particles are present. At 5,000x magnification, it can be seen that, as with the reference material and V21, cubic primary crystallites with edge lengths of around 200 - 300 nm are present. The SEM images clearly show that the LNCMO V5-Z is much finer than the reference material and LNCMO V21. This is confirmed by the optical particle size determination in the Mastersizer. The surfaces determined with BET correlate with these results. The different morphologies have a direct effect on the experimentally determined tap densities. The spherical powders of the reference and the LNCMO V21 have head densities of 2.44 g/cm^3 and 2.41 g/cm^3 respectively, whereas this value for the LNCMO V5-Z is only 1.64 g/cm^3. The chemical analysis revealed the following values:

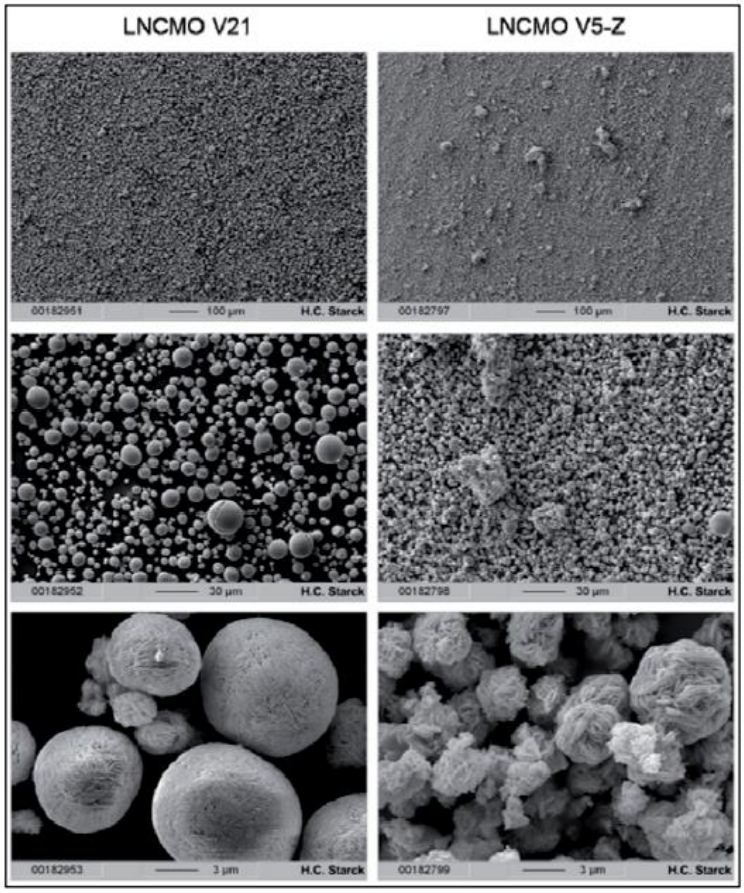


Figure C-2: SEM images of the precursors from recycled solutions at 200x, 1000x and 5000x magnification

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

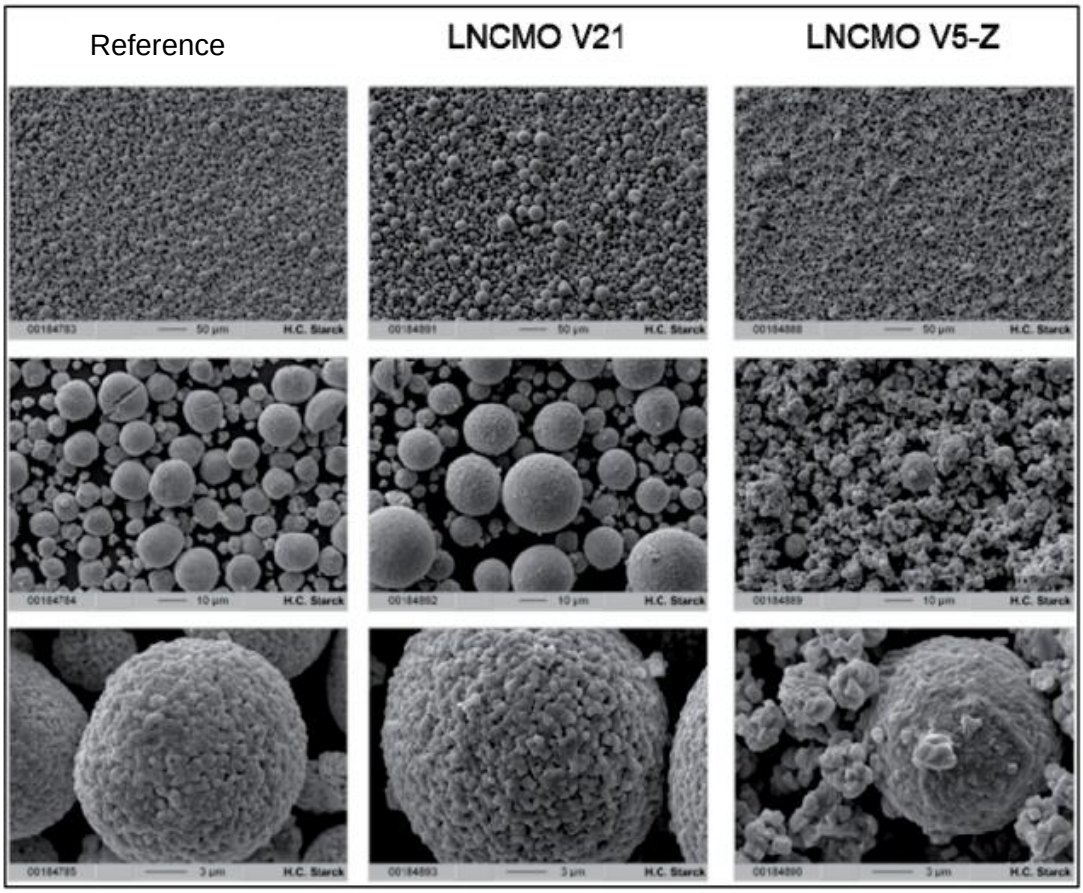


Figure C-3: SEM images of the reference material and the LNCAO materials from recycled solutions at 200x, 1,000x and 5,000x magnification.

Table C-8: Chemical composition of the active materials [mass%]

	H_2O according to Fischer [%]	CO_3 [%]	NO_3 [ppm]	Al [%]	Co [%]	Ni [%]	Cr [ppm]	Fe [ppm]	Li [%]	Mn [%]
Ref.	0.020	< 0.10	<20	0.01	20.00	20.00	<10	<10	7.60	18.00
V21	<0.02	< 0.10	<20	0.01	20.00	20.00	<10	<10	7.56	19.00
V5-Z	0.040	0.51	<20	0.57	18.00	18.00	<10	112	7.57	16.00

Accordingly, the material obtained from the recycling solution of the formed V21 has an almost identical composition to the reference. LNCMO V5-Z, on the other hand, shows significant differences.

The X-ray powder diffractograms of all three materials show the expected diffraction patterns and largely correspond to that of the lithium nickelate $LiNiO_2$. In addition, the diagram of LNCMO V5-Z shows a series of less intense and broad reflexes at 2Θ = 23°, 30° and 32.5°, which could not be assigned to any known phase so far. For electrochemical characterization, the first three charge and discharge cycles of the materials were examined using two cells each. The results can be found in Table C-9.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Table C-9: Charge and final charge capacities of two cells each of the reference LNCMO and V21 resp. V5-Z

	1. loading capacity	1. discharge capacity	*Efficiency*	2. loading capacity	2. discharge capacity	*Efficiency*	3. loading capacity	3. Discharge capacity	*Efficiency*
	[mAh/g]	[mAh/g]	*[%]*	[mAh/g]	[mAh/g]	*[%]*	[mAh/g]	[mAh/g]	*[%]*
	Cell 1								
Reference	175	157	*89.7*	156	157	*100.4*	156	150	*96.1*
V21	178	156	*8 7.5*	157	155	*98.7*	156	149	*95.7*
V5-Z	158	139	*87.9*	140	139	*99.2*	139	134	*96.2*
	Cell 2								
Reference	176	155	*88.1*	154	150	*97.5*	1)		
V21	176	156	*88.7*	157	152	*97.1*	1)		
V5-Z	160	140	*87.7*	140	140	*99.8*	139	134	*96.3*

1) Cell 2 of the reference and the V21 experienced measurement problems in the third charging cycle

In summary, it can be said that, according to the initial findings, competitive active material can be produced from the solution of the slightly contaminated V21 without further processing. The morphology and composition of both the precursor and the annealed active material correspond to those of the reference. The electrochemical performance is also identical - only marginal differences are observed during both charging and discharging.

In contrast to the reference and the LNCMO V21, there are clear differences in the chemical composition, morphology, tap density and electrochemical performance of both the precursor and the active material of the more heavily contaminated sample.

The finished $LiFePO_4$ samples were physically and chemically analyzed in detail according to Sued Chemie's standard internal quality assurance methods. Surprisingly, up to an impurity level of 20,000 ppm (Li_2SO_4 in LiOH), no significant difference in the chemical properties of the cathode material was found on a laboratory scale and on a pilot plant scale (see Table C-10). From these results it can be deduced that the sulphur limit in the LiOH raw material specification may be raised to 20,000 ppm.

Table C-10: Chemical, physical and electrochemical properties of LiFePO4 materials produced from secondary Li raw materials

Element	Lithium Sulfate content in LiOH (ppm)	Li (wt.%)	Fe (wt.%)	P (wt.%)	C (wt.%)	S (wt.%)	Specific capacity (mAh/g)
Specifications	---	4.55± 0.25	32.9± 0.8	19.1± 0.5	2.25± 0.25	<0.15	150±5.0
Lab LFP samples							
L1	0	4.6	33.4	19.1	2.1	0.05	147
L2	10	4.4	34.4	19.1	2.2	0.05	146

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

L3	500	4.3	35.0	19.2	2.1	0.05	152
L4	10,000	4.4	34.9	19.2	2.2	0.05	149
L5	20,000	4.3	34.5	19.1	2.0	0.05	154
Large LFP samples							
T1	0	4.3	34.6	18.9	2.2	0.08	148
T2	1,000	4.2	34.3	18.7	2.1	0.10	149
T3	10,000	4.2	34.6	18.8	2.1	0.10	149

C.3 Production and characterization of new electrodes and test cells from recycled active materials

At the end of the project, HCST was once again provided with approx. 10 l of a cyclized V-5Z solution ("third synthesis cycle") from a large-scale trial. The elemental analysis showed that the sample from the large-scale test had significantly lower Li and Cu concentrations compared to the originally supplied V5-Z solution. The lithium content was reduced by three quarters and the Cu content by a quarter. In contrast, the Al content was identical to the first sample.

As a result, the problems already listed in **AS C.2.3** occurred again during the hydrometallurgical production of the precursor. This resulted in the precipitation of aluminum hydroxide, which interfered with the precipitation of the transition metal hydroxides and stuck them together. For this reason, the synthesis of the active material by adding the Li component and the calcination step was not pursued further.

C.3.1 Standardized electrode and cell production from commercial reference materials and electrochemical characterization

T-cells (Swagelok) were manufactured in accordance with the specifications agreed between IPC-WWU and iPAT-TUBS. For this purpose, the components were mixed dry, dispersed in NMP and then the electrodes were manufactured. Figure C-4 shows a cyclization curve of $LiFePO_4$ in a T-cell. A clear drop in efficiency can be seen after approx. 30 cycles. Experience has shown that approx. 500 cycles are achieved in such a test arrangement. These fluctuations are attributed to contamination of the electrolyte used and leaks in the cells used. To optimize and avoid further contamination, the electrolyte was replaced with EC/DMC and $LiBF_4$. The new cyclization with $LiBF_4$ as conductive salt in EC/DMC shows higher cycle stability of over 500 cycles compared to the previous material. Therefore, all comparative measurements are performed with this electrolyte. Figure C-5 shows the corresponding DC rate test.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

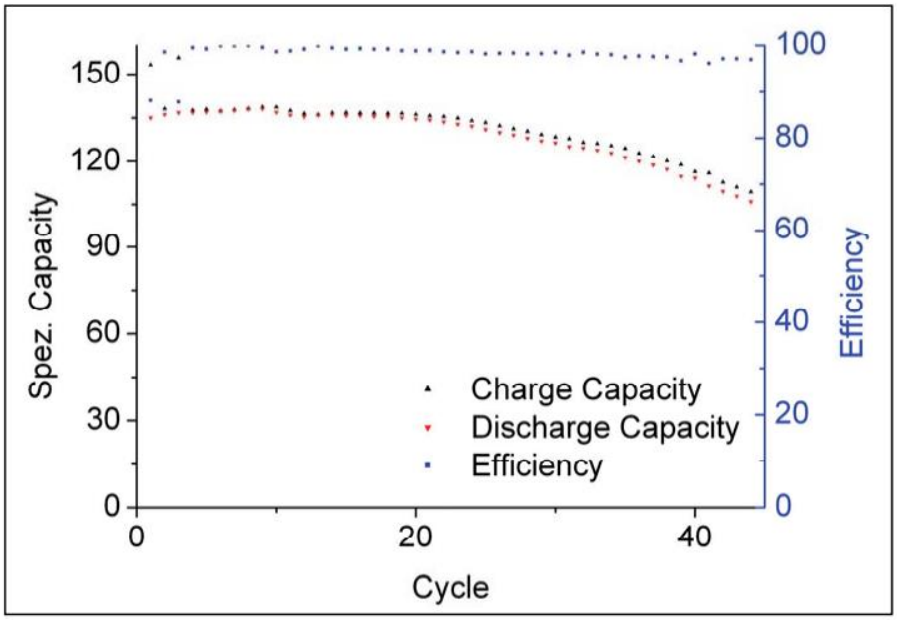


Figure C-4: Cycling curve of LiFePO4 at room temperature

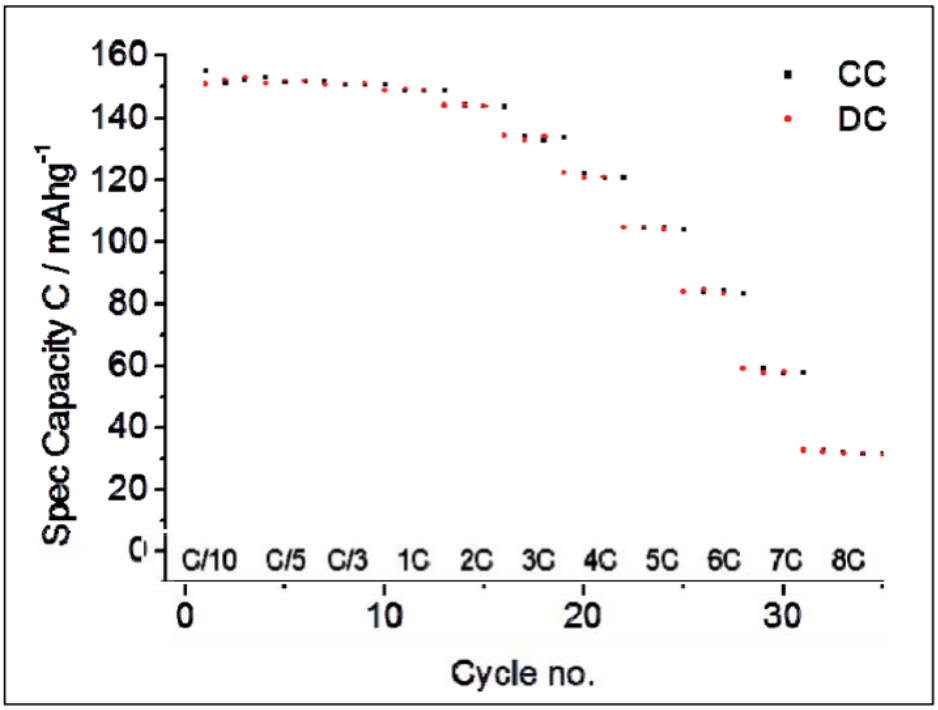


Figure C-5: DC rate test of $LiBF_4$ in EC/DMC

Several reference electrodes and reference cells were manufactured by iPAT-TUBS and LTA and compared with each other in agreed electrochemical cycling routines. The most important electrochemical characteristics for use in automobiles - current carrying capacity and cycle stability. The reference data provided by LTA are shown in Figure C-6 and Figure C-7. The cycling routine used begins after the formation with a current stability test in the first 30 cycles (see Figure C-7). The cell is initially charged at a rate of 0.5 C. This is followed by charging and discharging rates of 1 C, 3 C, 5 C, 10 C, 0.5 C, 1 C and 3 C. Subsequently, the cycle stability is tested by continuous charging and discharging at 3 C up to the 500th cycle. cycle is

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

determined.

The reference system has a stability of 95% of its capacity after 500 cycles. The relative capacitance at rates of 3 C and 5 C in relation to the capacitance at 0.5 C are particularly relevant for the ampacity test. Thus, at charge/discharge rates of 3 C, the reference cell still has 89% of its capacity at 0.5 C and at 5 C it still has 74% of the value at 0.5 C.

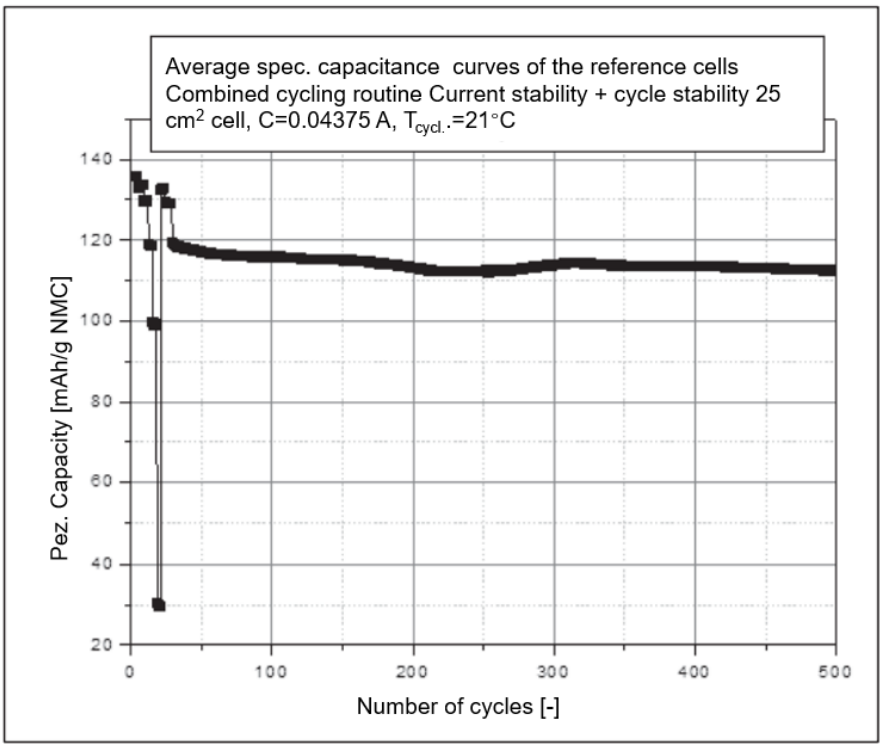
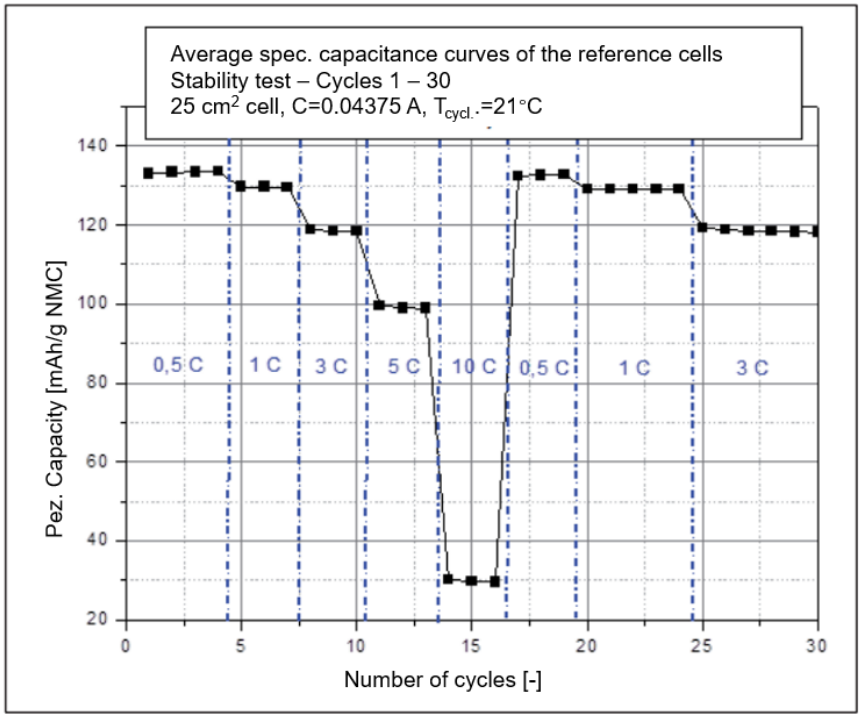


Figure C-6: Electrochemical cycle test of a reference cell made of new materials - current stability test (cycles 1-30) and cycle stability at 3C (cycles 30-500)



This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure C-7: Electrochemical cycle test of a reference cell made of new materials - characterization of current stability at varying charge rate

The test scenarios used here are used to specify electrodes and cell chemistry for use in the automotive industry. The test scenarios used are therefore relevant in practice and also characterize the electrochemical behaviour of battery cells at the highest level.

C.3.2 Standardized electrode and cell production from reconditioned active materials and electrochemical characterization

In **AS C.3.2,** reconditioned active materials recovered from non-cyclized rejects from the LTA and from cyclized electrodes were tested. For this purpose, anode and cathode materials obtained from the separation and preparation in **AP B.3** were processed into new electrodes on a laboratory scale by iPAT-TUBS and assembled into full cells (25 cm^2) by LTA. Three cathode powders from two different processes were supplied to LTA by iPAT-TUBS. These powders were used to manufacture electrodes according to the standard laboratory procedure of iPAT-TUBS and LTA. Figure C-8 shows the capacity curves of the reconditioned materials from the mechanical separation.

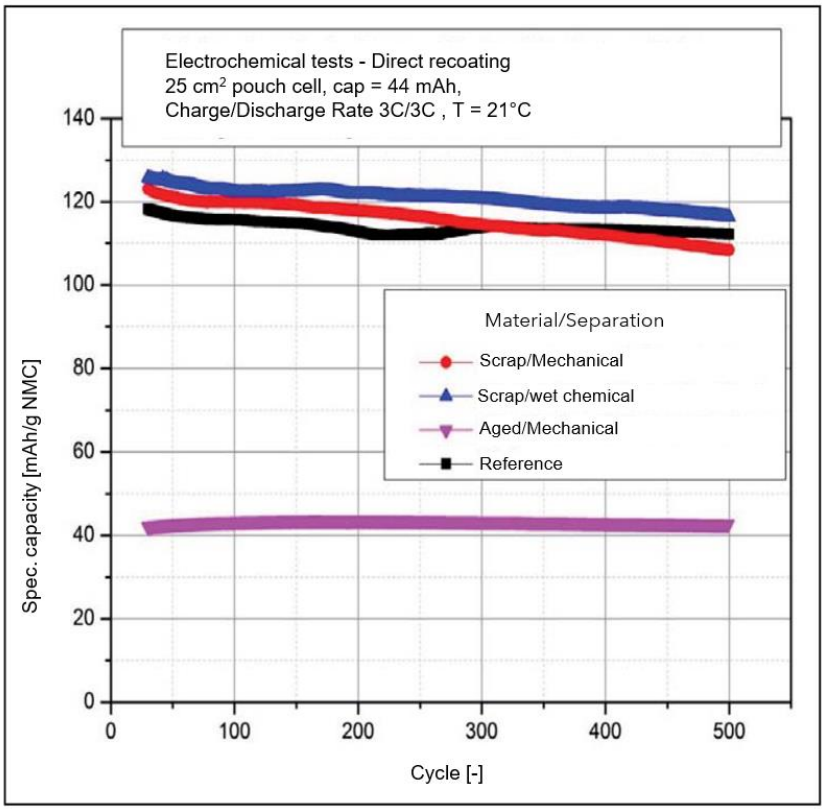


Figure C-8: Electrochemical capacitance curves of reference and cyclized materials

The electrochemical cycle tests performed in the iPAT-TUBS showed increased current stability with an admixture of 2% by weight of conductive carbon black to the reconditioned scrap materials. A higher admixture proportion of 4 wt.% conductivity additive, on the other hand, had a counterproductive effect on the specific capacity of the cell, as one of three cells lost a disproportionately large amount of capacity during cyclization, while the other two exhibited very high current stability. A lower dosage of 1 wt.-% had only minor effects.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

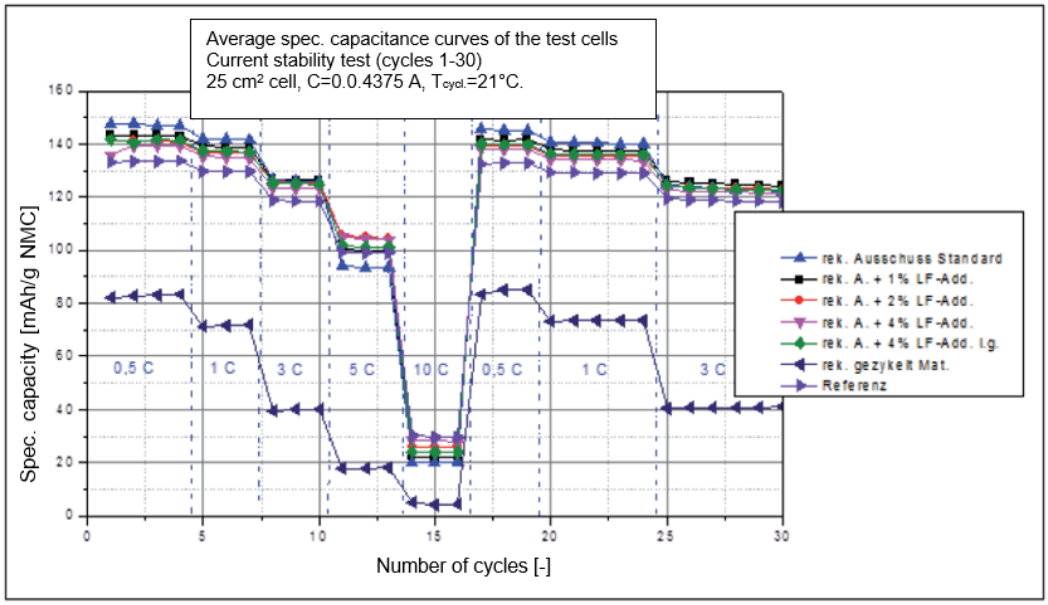


Figure C-9: Current carrying capacity test of reconditioned materials

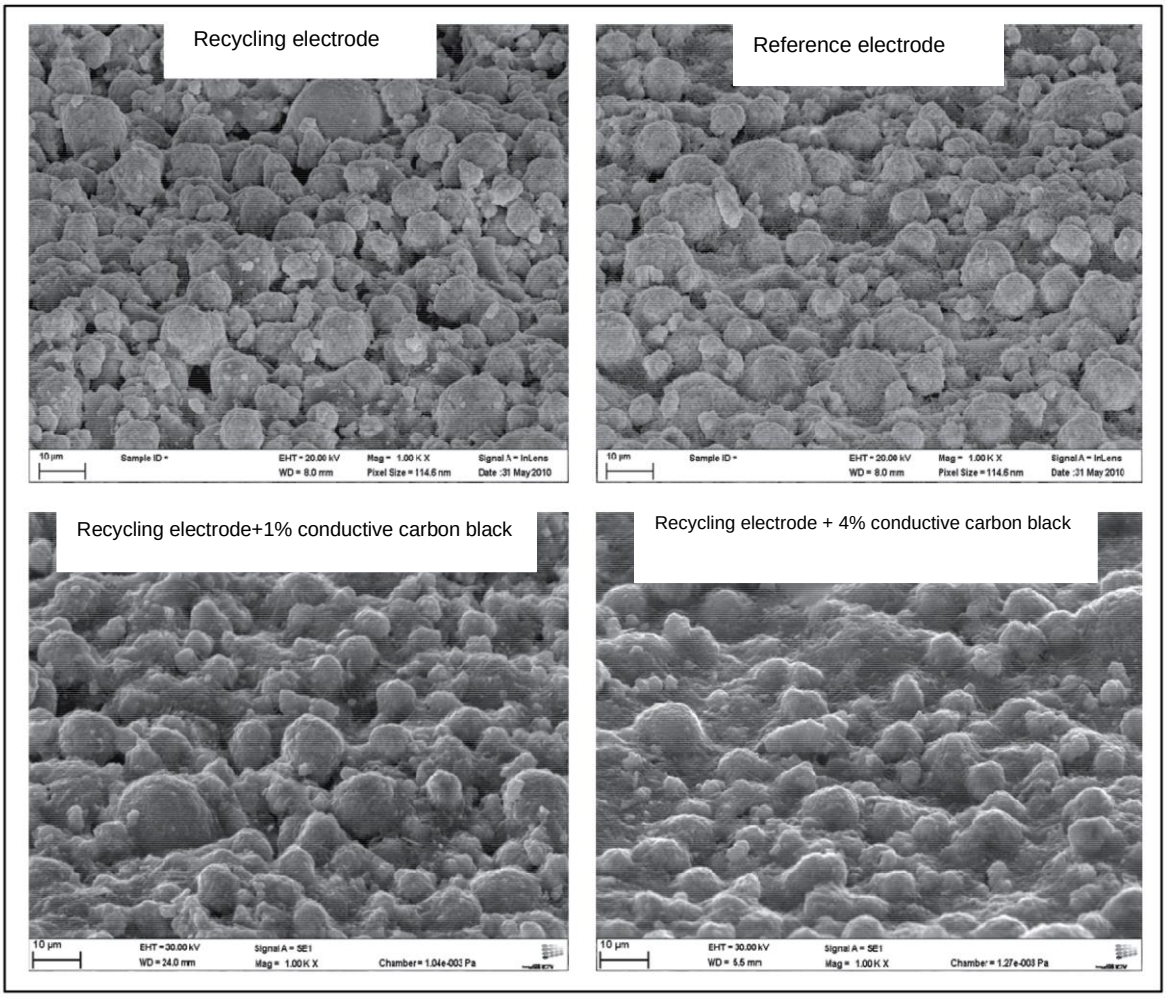


Figure C-10: Secondary electron micrographs of the surface of reconditioned electrodes, angle 60°(Source: IPC-WWU and iPAT-TUBS)

SEM images of the relevant electrodes provide an explanation for the observed improvements.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The reference electrode (top right) shows a clearly pronounced network consisting of conductivity additive and binder on its surface, while clear fissures are visible on the surface of the recycling cathode. This grid ensures good electrical conductivity and therefore better current stability. By adding conductive carbon black to the formulations of the recycling electrodes, this conductive network can be made more pronounced again (Figure C-10, lower images).

C.3.3 Standardized electrode and cell production from recycled active materials obtained from formed cells and electrochemical characterization

With the exception of the small quantity of V21 originally supplied, HCST recycling solutions from formed cells were not available.

The work steps **AS C.3.3** and **AS C.3.4** were not processed by LTA for the reasons stated in **AS C.3.1**. However, the samples were analyzed and tested in the cell systems at IPC-WWU.

The slightly contaminated material was first measured using BET. Only minor deviations between the reference and the sample with the slight contamination were detected. Furthermore, XRD measurements did not reveal any significant differences between the materials. SEM investigations (Figure C-11) have shown that compounding is still very pronounced in the case of light impurities.

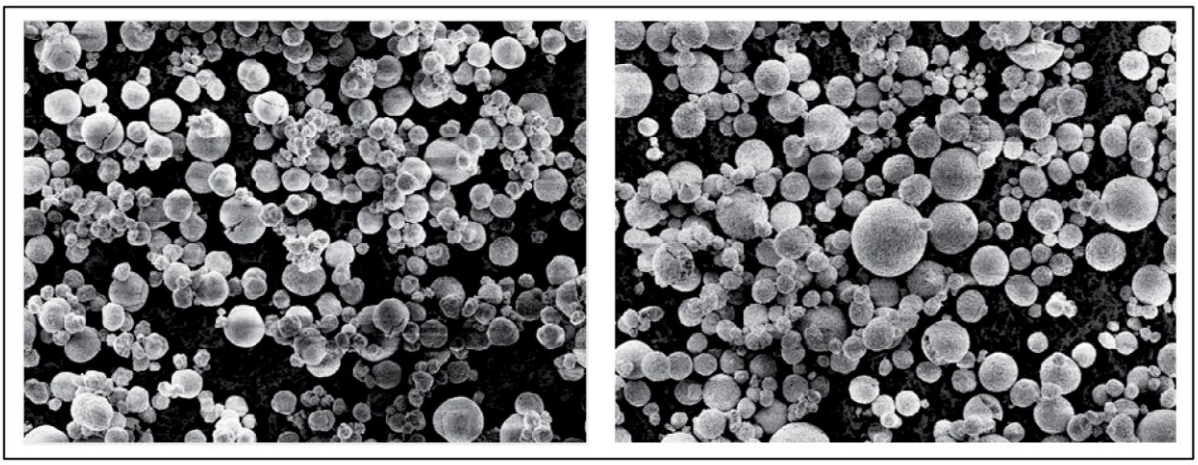


Figure C-11: Reference (left) and light contamination (right)

CV tests (Figure C-12) were also performed. As is usual for NMC, the oxidation potentials are around 3.7 V.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

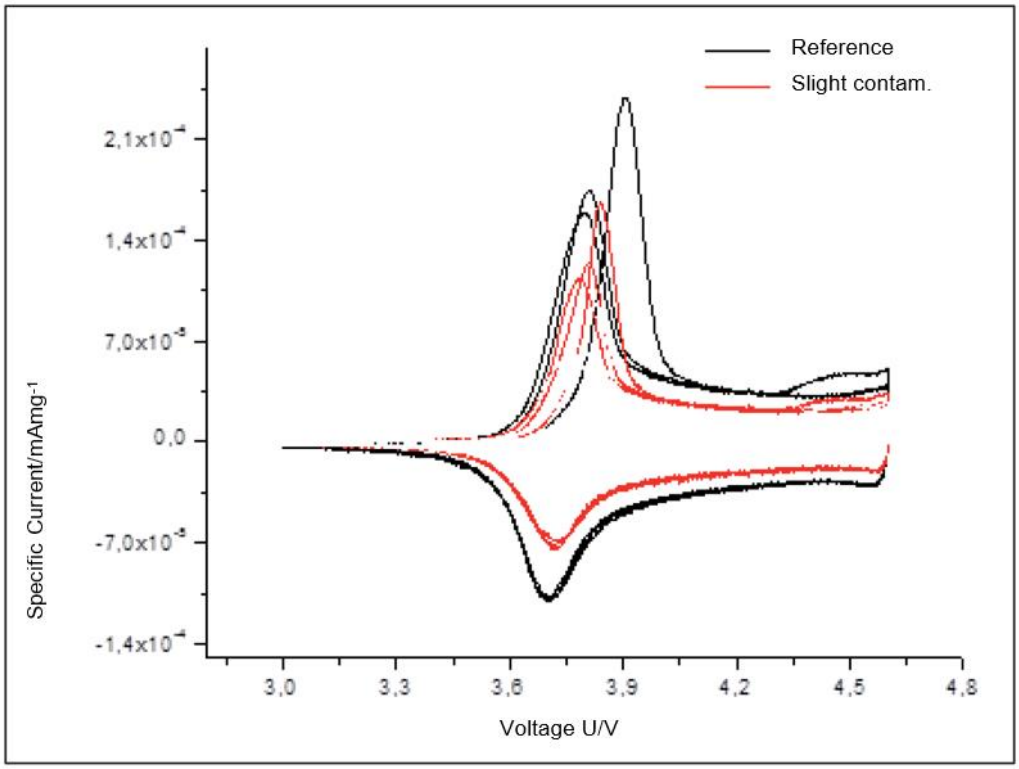
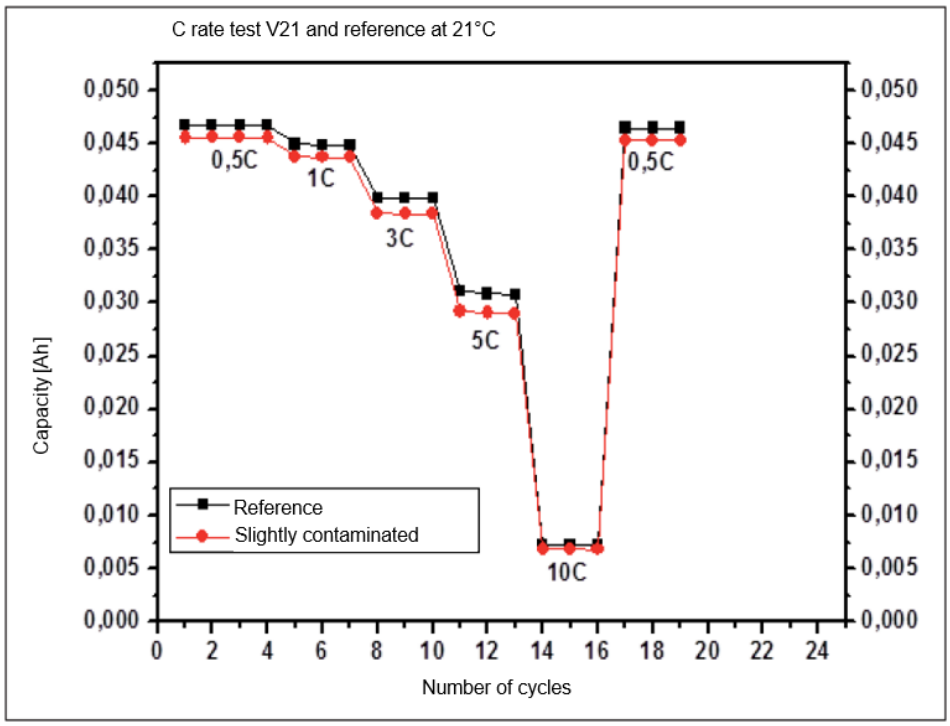


Figure C-12: CV test

Overall, the slightly contaminated material shows only slight deviations from the reference.

In **AS C.3.3**, recycled active material from formed cells was processed by the iPAT-TUBS into new electrodes and installed by the LTA into full cells (25 cm^2 active material area). 475 cycles with a charge/discharge current of 3 C were performed to investigate the long-term stability of the contaminated material in relation to an uncontaminated reference material (see Figure C-14).



This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure C-13: C-rate test V21 and reference

The current carrying capacity of the two samples examined here is very similar. The difference in performance is only a few percent and is almost the same for all discharge rates between 0.5 C and 10 C (see Figure C-13).

The cycle stability of the contaminated material is better than that of the reference material. Although this starts with approx. 10% higher capacity after the current load test, the capacity falls below that of the contaminated material after approx. 150 cycles. The capacity of the reference is still 70% of the original value after 475 cycles. The contaminated material still has 79% of its original capacity at the end of the performance test.

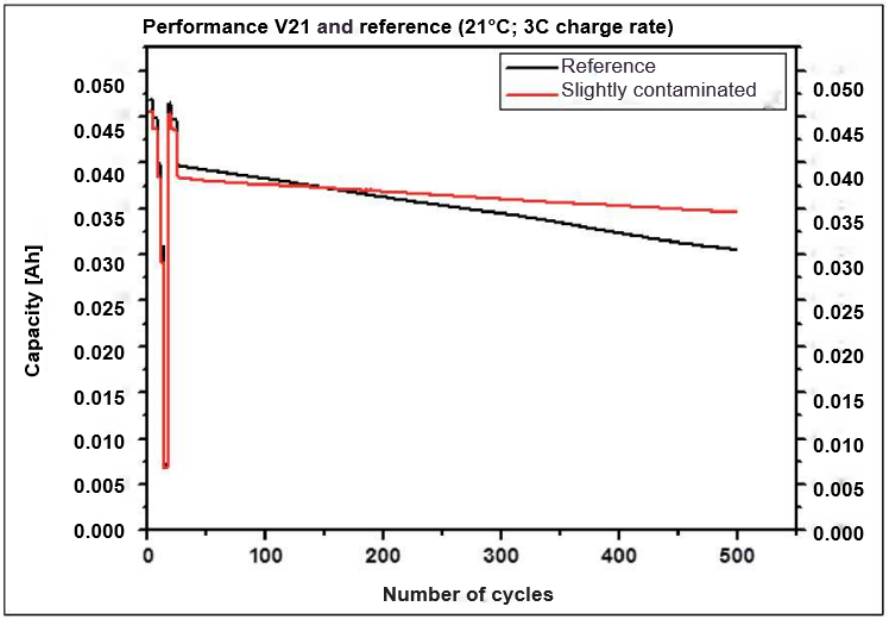


Figure C-14: Performance V21 and reference

Accordingly, minor impurities can be tolerated during the new synthesis of the active materials.

C.3.4 Standardized electrode and cell production from recycled active materials obtained from aged cells and electrochemical characterization

HCST provided approx. 10 l of a V5-Z solution ("third synthesis cycle") from a large-scale experiment and approx. 15 kg of sample material (precursor), which was intended for the production of electrodes and test cells.

Table C-11: Comparison of the composition of the reaction solution of V5-Z from the original (small-scale) experiment and the third synthesis cycle

	LNCMO V5-Z small-scale test [g/l]	LNCMO V5-Z Third cycle [g/l]
Li_2SO_4	38.02	10.85 [1)]
$NiSO_4$	76.46	76.46

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

	LNCMO V5-Z small-scale test [g/l]	LNCMO V5-Z Third cycle [g/l]
$CoSO_4$	76.57	76.57
$MnSO_4$	74.60	74.60
$Al_2(SO_4)_3$	6.98	7.34
$CuSO_4$	1.93	1.45
$FeSO_4$	0.060	- -
$MgSO_4$	0.12	- -

[1)] In the third cycle, no Li2SO4 was added but the equivalent amount of LiOH

Table C-11 shows a direct comparison of the solution for the third cycle with the solution originally used for the synthesis of LNCMO V5-Z. The sometimes significant differences are easy to see.

However, the same problems occurred in the hydrometallurgical representation of the V5-Z in the third cycle as in the small-scale test. In addition to the expected transition metal hydroxides, finely dispersed aluminum hydroxide also precipitated, which on the one hand interfered with the precipitation of the Ni/Co/Mn mixed hydroxide and on the other hand agglutinated the precipitated particles. The particle size distribution tests yielded the same results as those originally obtained in the small-scale test. With increasing reaction time, the proportion of fine particles even increased, resulting in a bimodal particle size distribution. This fact once again indicates that, with regard to recycling the active materials on the cathode side, efforts to deplete the aluminum in the transition metal solutions must remain a priority in the future.

For this reason, further processing of the precursor, in particular the addition of lithium carbonate and subsequent calcination and final processing, was not pursued further. Therefore, neither standardized electrodes nor cells could be manufactured from this barrel.

During the visual inspection of the material, a strong decrease in bulk density could already be observed, which is dependent on the degree of contamination. The surface was therefore characterized with the help of BET measurements. Compared to the reference, a significantly increased surface area is shown for the material with the heavy contamination. This may be due to poorer compounding. To check this point, further SEM recordings were made. XRD measurements were performed to detect possible foreign particles. The measurements show clear impurities that can impair performance, which becomes apparent in later experiments.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

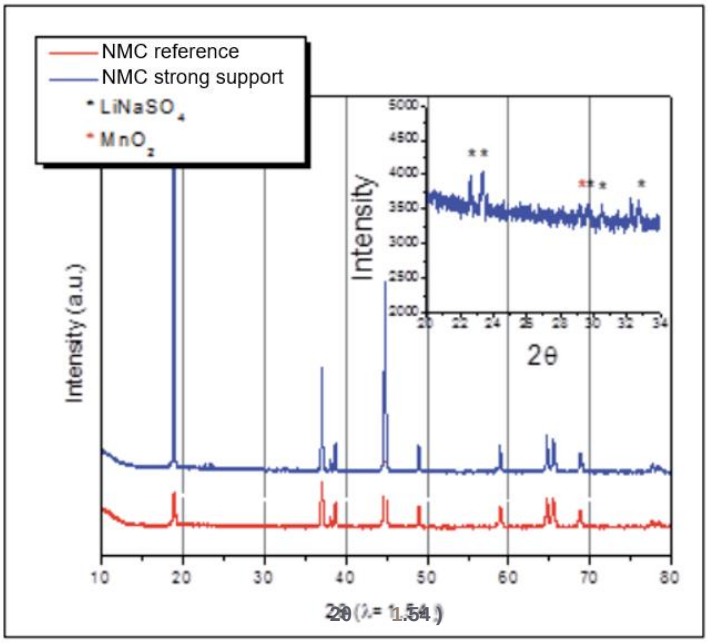


Figure C-15: XRD measurements

SEM measurements were performed to deepen the previous findings. This shows that in the case of heavy contamination, the material is almost exclusively present as primary particles. This impairs the electrical contact in the electrode, as smaller particles can be insulated by the complete inclusion of binder material, for example. This would result in a lower electrical capacity.

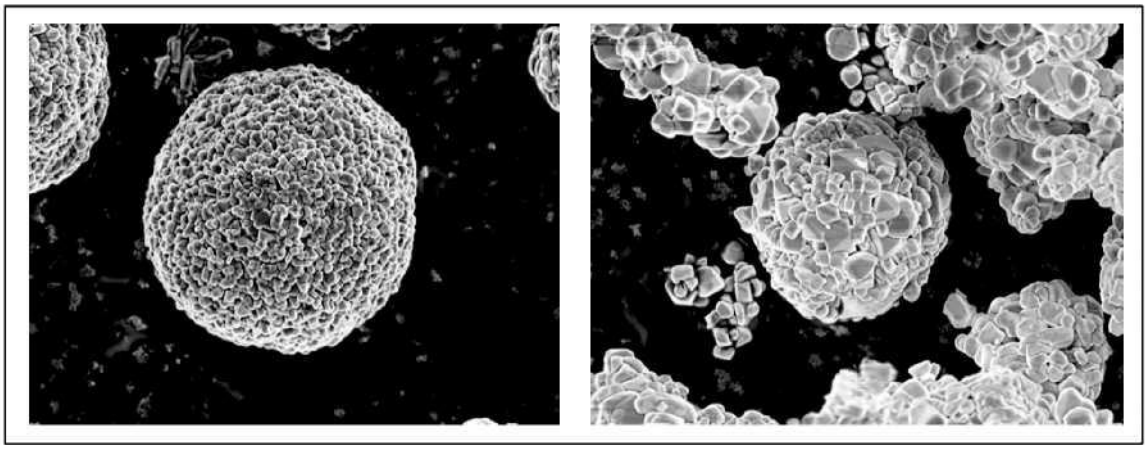


Figure C-16: View of the primary particles in the reference (left) and heavy contamination (right)

In the heavily contaminated sample, the compounding of the primary particles into a secondary agglomerate is only faintly recognizable.

For the CV test, the cyclic voltammetry data were related to the mass of the active material in the electrode. As is usual for NMC, the oxidation potentials are around 3.7 V. It is interesting to note that the voltage of the reference material rises to 3.9 V at the oxidation peak. However, this is not the case with the contaminated materials. The increase can occur more frequently with NMC, so it is not unusual. What unfortunately also becomes clear here, however, is that the capacity (area under the curves) will decrease with increasing contamination.

The work steps AS C.3.3 and AS C.3.4 were not processed by LTA for the reasons stated in AS C.3.1. However, the samples were analyzed and tested in the cell systems at IPC-WWU. For the electrochemical analysis of the “recycled” LiFePO4 samples in full cells, the corresponding samples were sent to IPAT-TUBS.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

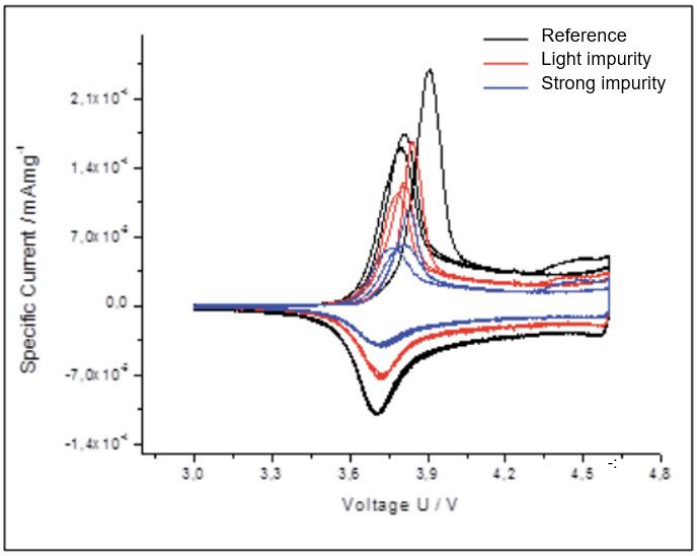


Figure C-17: CV data of all three materials

The trend described above is clearly confirmed by investigations into cycle stability (Figure C-17): The specific capacity decreases with increasing contamination, but even the heavily contaminated material can be cycled at a respectable capacity of 115 mAh/g with very little fading. The efficiency after the first cycle is 79% for the reference and 83% and 80% for the light and heavy contamination respectively. The corresponding Figure C-18 shows an overview of the overall cycle stability. The C-rate test further confirms the previous trend of increasing contamination.

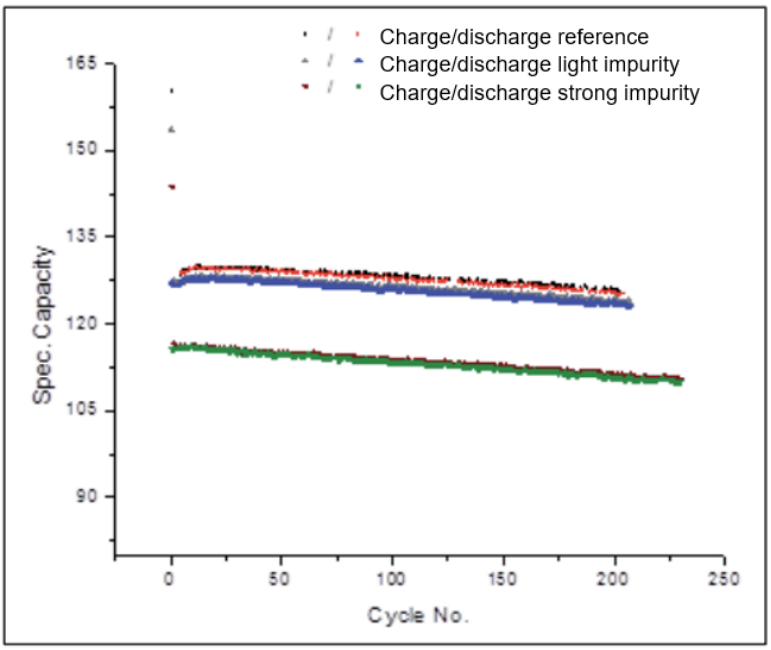


Figure C-18: Cycle stability

The work steps **AS C.3.3** and **AS C.3.4** were not processed by LTA for the reasons stated in **AS C.3.1**. However, the samples were analyzed and tested in the cell systems at IPC-WWU. For the electrochemical analysis of the “recycled” LiFePO4 samples in full cells, the corresponding samples were sent to IPAT-TUBS.

More contaminated material was used in **AS C.3.4** than in **AS C.3.3**. The processing in this step is identical to that in **AS C.3.3.** The electrochemical characterization included a current load test after forming the cells (see Figure C-19) and then 475 cycles with a current of 3 C to determine the cycle

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

stability (see Figure C-20). The current load test shows a clear difference in the performance of the two materials. With the exception of the 10 C charging current (here the capacity of both cells is close to zero), the heavily contaminated material is always 15 - 20% below the capacity of the reference material. The cycle stability of the heavily contaminated material is significantly lower than that of the reference material. After just 50 cycles, the capacity drops to approx. 55%, then stabilizes at this value and continues to change until the 500th cycle. cycle is no longer significant. As analyzed by HCST, the two samples V21 and V5-Z differ mainly in the copper, iron, aluminum and carbonate content. It can therefore be concluded that these elements or compounds have a significant negative impact on the performance of the cell. The recommendation would be to eliminate or at least significantly reduce the proportion of these compounds before producing the new active material.

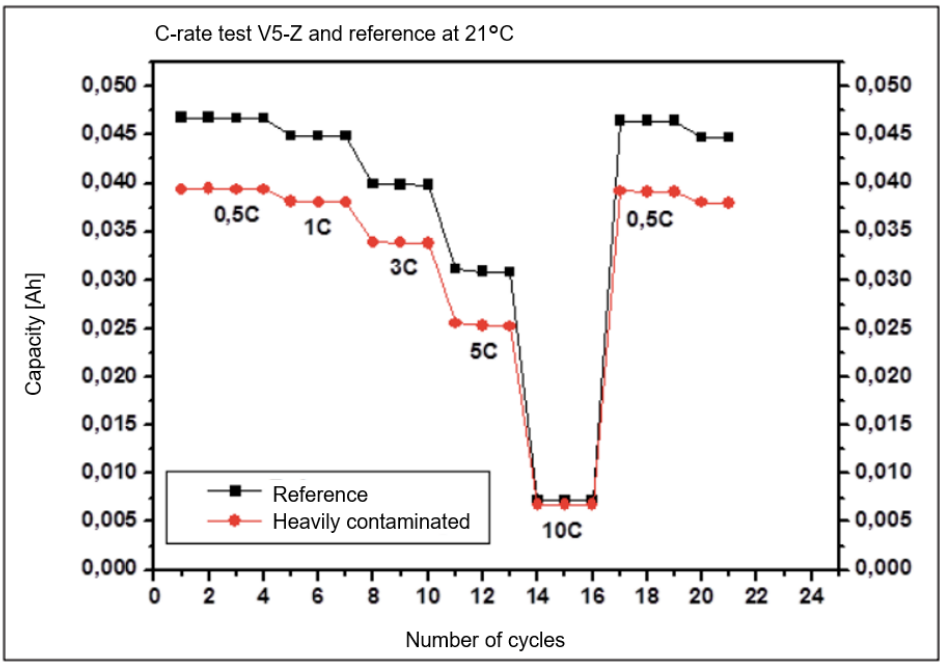


Figure C-19: C-rate test V5-Z and reference

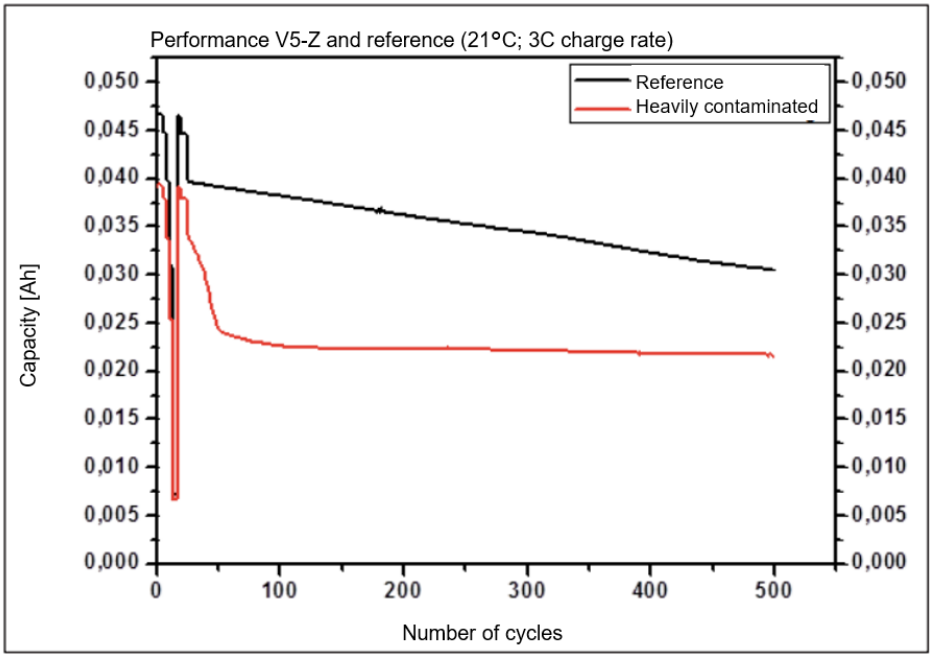


Figure C-20: V5-Z Performance and Reference

The observations in **AS B.3.1** suggest that the contamination with aluminium does not have a direct effect on the results of the electrochemical cyclization. It was observed that the

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

reconditioned materials showed equivalent performance to the virgin materials, even though they were also contaminated with approximately one percent aluminum by weight. However, Al contamination (see HCST **AP C.2**) has a negative effect on the hydrometallurgical process for precipitating the transition metal hydroxide particles and significantly influences their particle size and morphology. In addition, aluminum contents > 1 wt.% cause losses during the renewed production of active material from the transition metal salt solution, since colloidally distributed aluminum hydroxide leads to the metal hydroxide particles sticking together and thus makes grinding of the agglomerates in the jet mill considerably more difficult.

D Analysis of the aging behavior of Li-ion batteries

In **AS D.1**, the performance of standard active material for lithium-ion cells was recorded and these cells were then subjected to a post mortem analysis. The mechanical properties of the electrode, such as adhesive force and elasticity of the coating, were measured. Cyclization deteriorates the mechanical properties of the electrode depending on the charging current and the temperature at which the cell was charged. A standard cell system consisting of ten round cells was also examined. After an initial characterization of the cells, it was determined how these cells behave during a current jump. In addition, the behavior of these cells during a deep discharge was investigated and to what extent the cells can be reactivated after a deep discharge. The exact results for **AS D.1** can be found in section D.1.

The performance of recycled materials, which were processed into electrodes in **PB C**, was then recorded in **AS D.2**. These electrodes were then also subjected to a post-mortem analysis and the mechanical properties were examined. Two NMC active materials with different levels of contamination were tested. The slightly contaminated material performs just as well as the uncontaminated standard material. On the other hand, the heavily contaminated material stood out due to its reduced performance. However, the mechanical properties of the aged electrodes differ only slightly, so it is reasonable to assume that the reduced performance can be explained by the different particle size and morphology. However, this could not be investigated further due to a lack of comparative possibilities.

Step **AS D.3** compares and analyzes the results of **AS D.1** and **AS D.2**. The results can be found in section D.3.

D.1 Recording the performance and analyzing the aging of conventionally available active materials using a standard cell (LiFePO4 and layered oxides)

The aim of this project area is to record the performance data of the reference materials at different temperatures and charge and discharge rates and to compare them with the data of cells made from recycled active materials. Figure D-1 shows an example of a cycling curve of commercial $LiFePO_4$ at a temperature of 40°C and a charge/discharge rate of 1 C. The cell shows good cycle stability, achieving well over 450 cycles.

Figure D-2 shows the cyclization of NMC rejects. The performance of the reconditioned rejects is slightly worse than the reference. The optimization is performed by the corresponding project partner.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

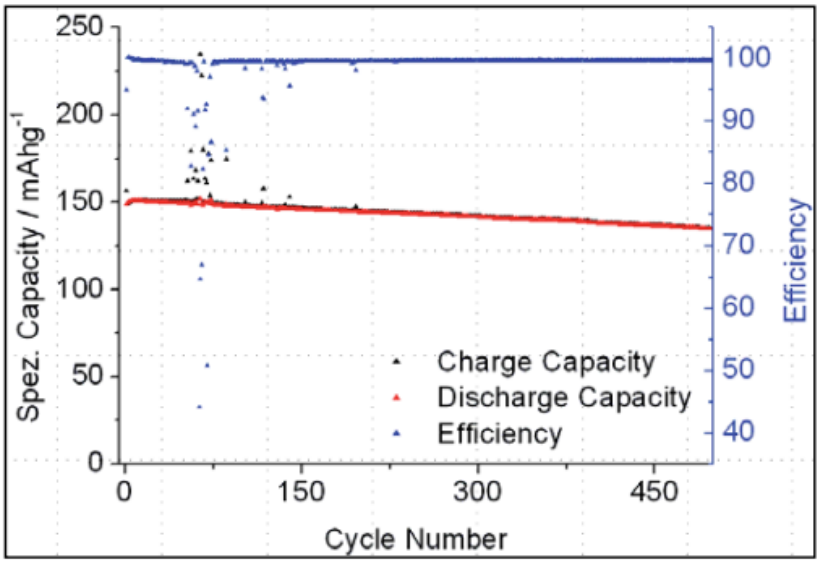


Figure D-1: Cycling curve of LiFePO4 at 40°C

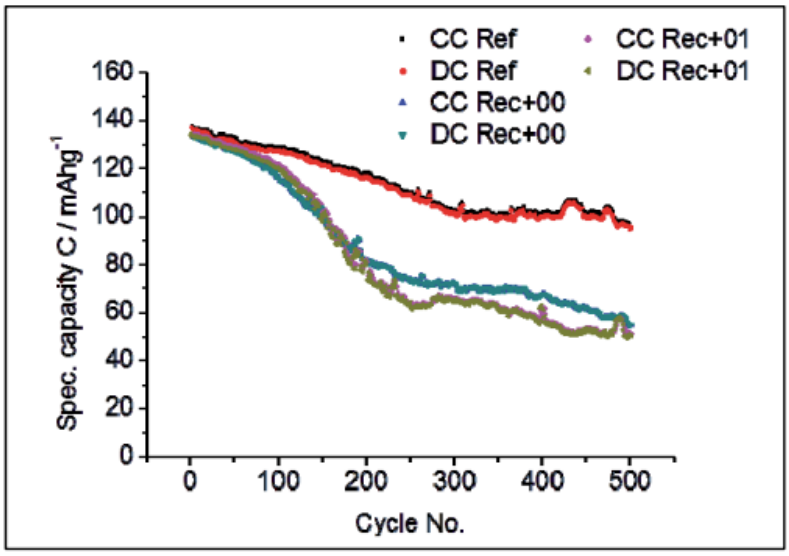


Figure D-2: Cycling curve of NMC at 40°C

The other figures show the tests on aging behavior according to Table D-1:

Table D-1: Matrix of ageing tests

	1CCC	3CCC	DST
RT			-
35°C			-
45°C			-

The aging behavior of the reference material is as expected, the processing of the matrix is complete.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

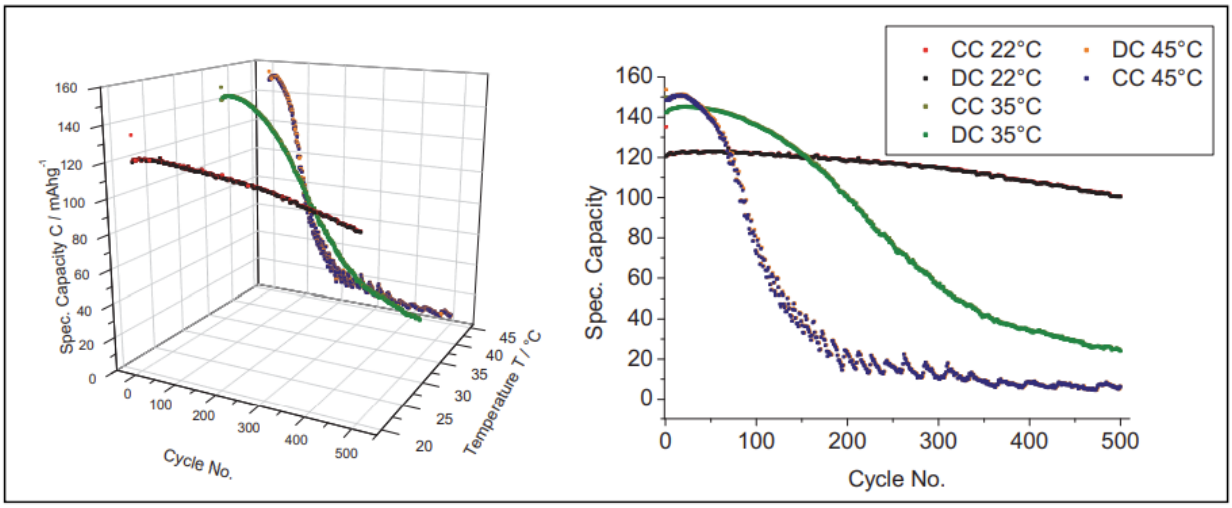


Figure D-3: Temperature matrix 1CCC with LiBF4 in EC/DMC

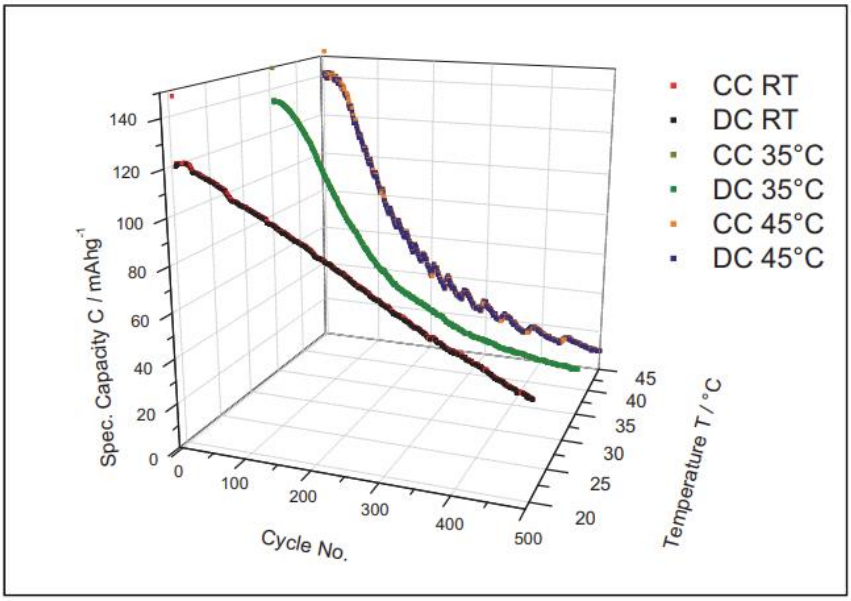


Figure D-4: Temperature matrix 3CCC with LiBF4 EC/DMC

Characterization

As part of **AS D.1**, standard cells were characterized by HTEE-TUBS. A capacity test was first performed for this purpose. The test system consists of ten LFP round cells. These are connected in series and are monitored by a battery management system.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

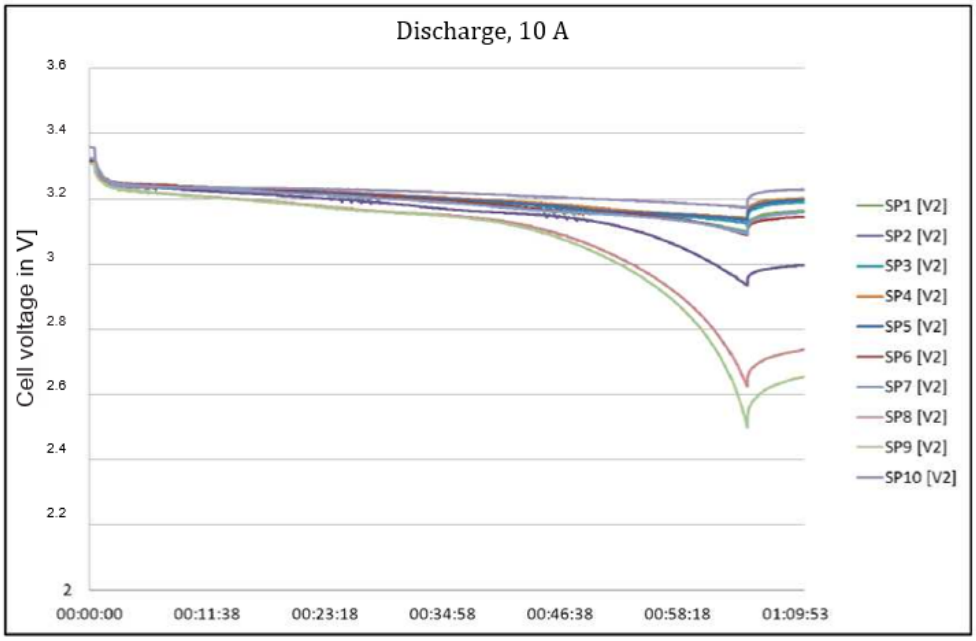


Figure D-5: Discharge of the standard cells to be characterized

The termination criterion for discharging is when the cell voltage falls below 2.5 of Until this cell voltage is reached, 10.777 Ah is discharged. A charging process is then started, the cell voltage curve of which is shown in Figure D-6. The termination criterion is when a maximum cell voltage of 3.6 V is reached. This is achieved after 10.829 Ah have been charged. The discharge/charge efficiency of the system is therefore η = (10.777/10.829) * 100% = 99.5%. An inhomogeneous distribution of the state of charge between the individual cells can be observed. While the lower end-of-discharge voltage of cell 9 (SP 9) is reached during discharge, the upper end-of-charge voltage of cell 10 (SP 10) is reached first.

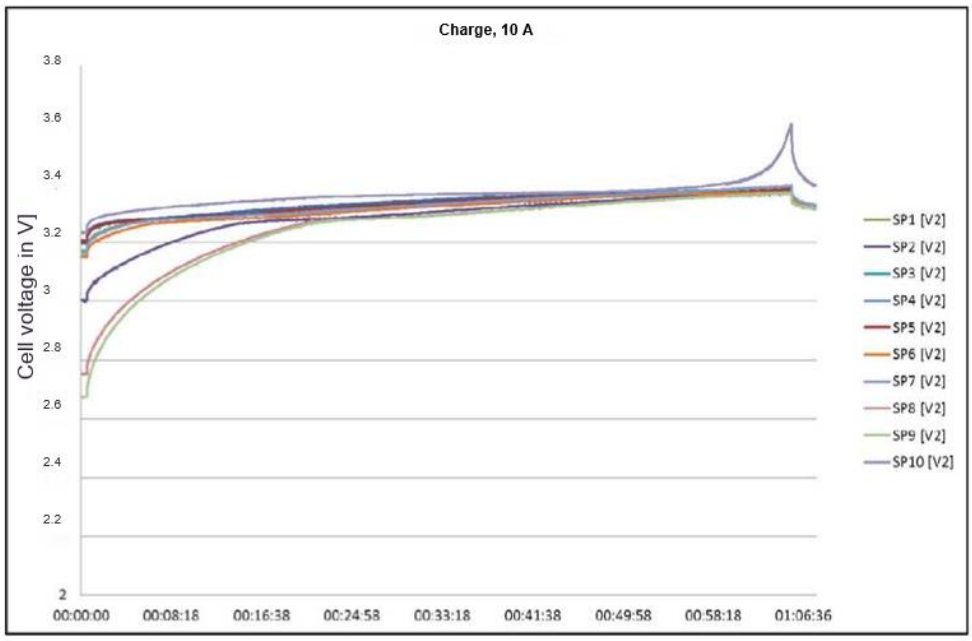


Figure D-6: Charge of the standard cells to be characterized

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Determination of the step response for characterization

In addition to characterizing the standard cells through a capacity test to determine the usable capacity and efficiency, the system is subjected to a current pulse and the resulting step response is determined. Figure D-7 and Figure D-8 show the step response of the overall system and the individual cells to a current pulse of 85 A.

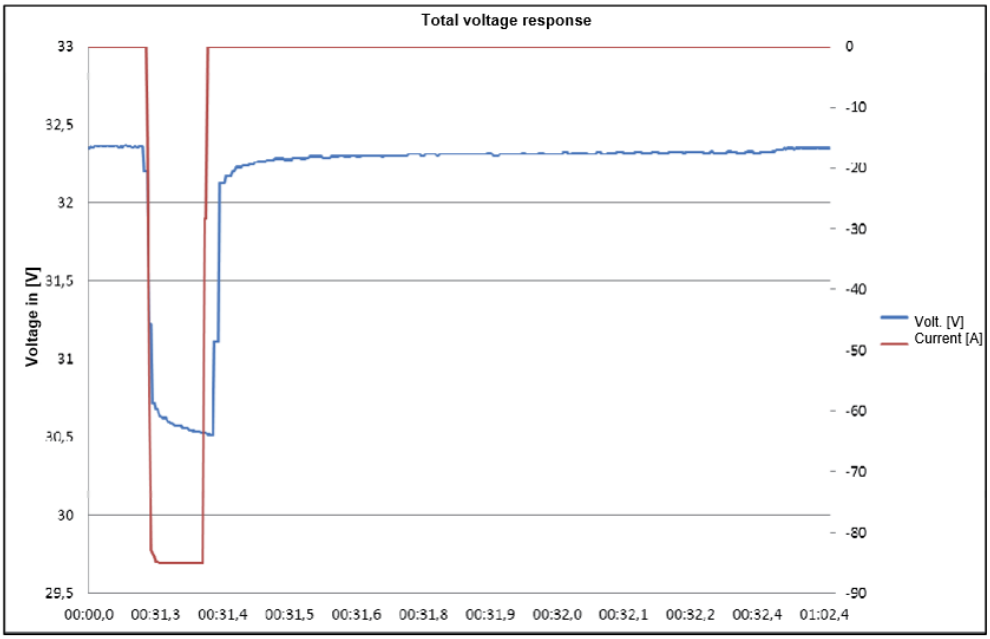


Figure D-7: Step response of the total voltage of the system

The step response of the total voltage is used to evaluate the suitability of the system for highly dynamic applications. The analysis of the individual cell voltages shows the scattering of the state of the cells in the system.

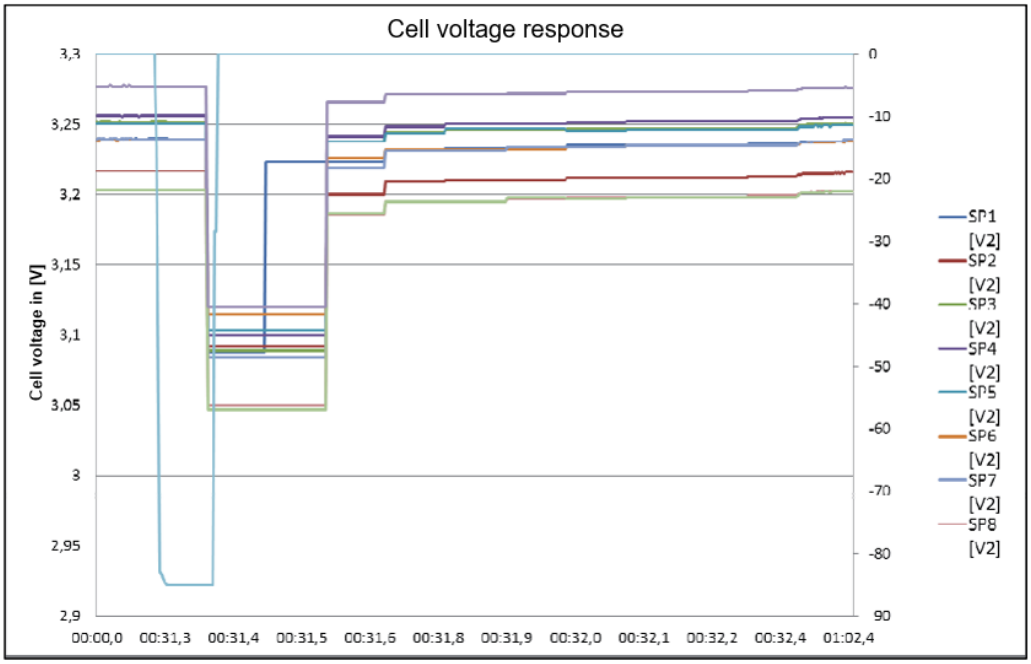


Figure D-8: Step response of the single cell voltages

This characterization was performed on other standard cells in order to increase the database

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

for the evaluation of recycled battery cells.

Reaction to deep discharges

Deep discharge is an operating condition that should be avoided and has a negative impact on the performance of a battery system. Deep discharge by a consumer is prevented by monitoring by the battery management system. Nevertheless, deep discharge during long periods of inactivity cannot be ruled out due to the self-discharge of the battery cells and the self-consumption of the battery system. This operating state is therefore simulated using a battery system as an example and the effects on the condition of the battery system are investigated. The battery system is stored for six weeks with the BMS switched on. After this time, a cell voltage < 0.5 V per cell was detected. To restart the system, it was charged with a low current of 0.1 A for 1 min. Once functionality was established, the system was charged further with a current of 0.5 A. Charging initially takes place up to a level of 3.0 V

An internal resistance test is performed using a charging and discharging pulse. A high voltage jump on a single cell is noticeable. Since this can be observed equally during the charging and discharging pulse, this confirms the assumption of an increased internal resistance of the cell.

Following this test, the system is discharged with a constant current of 10 A. The discharged capacity is > 40 Ah, which is above the nominal capacity of the battery system.

Due to the deep discharge of the system, one cell of the four cells in the system was particularly damaged. The usable capacity of the battery system is still higher than the original nominal capacity of the battery system. Three of the four cells in particular can therefore still be used. Information about the existence of a deep discharge is therefore not sufficient for deciding how to handle individual battery cells. Other factors such as the duration of the deep discharge state play a major role here.

The findings from **AS D.1** have been incorporated into the development of the test procedure in **AS A.4.4**.

Cyclization

Furthermore, standard cells with standard profiles were cyclized as part of **AS D.1**. The standard cells were then unloaded and transferred to **PB B** for opening and further processing.

Figure D-9 shows the course of the cell voltages during cyclization. These show a clear scattering of the charge states during cyclization.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

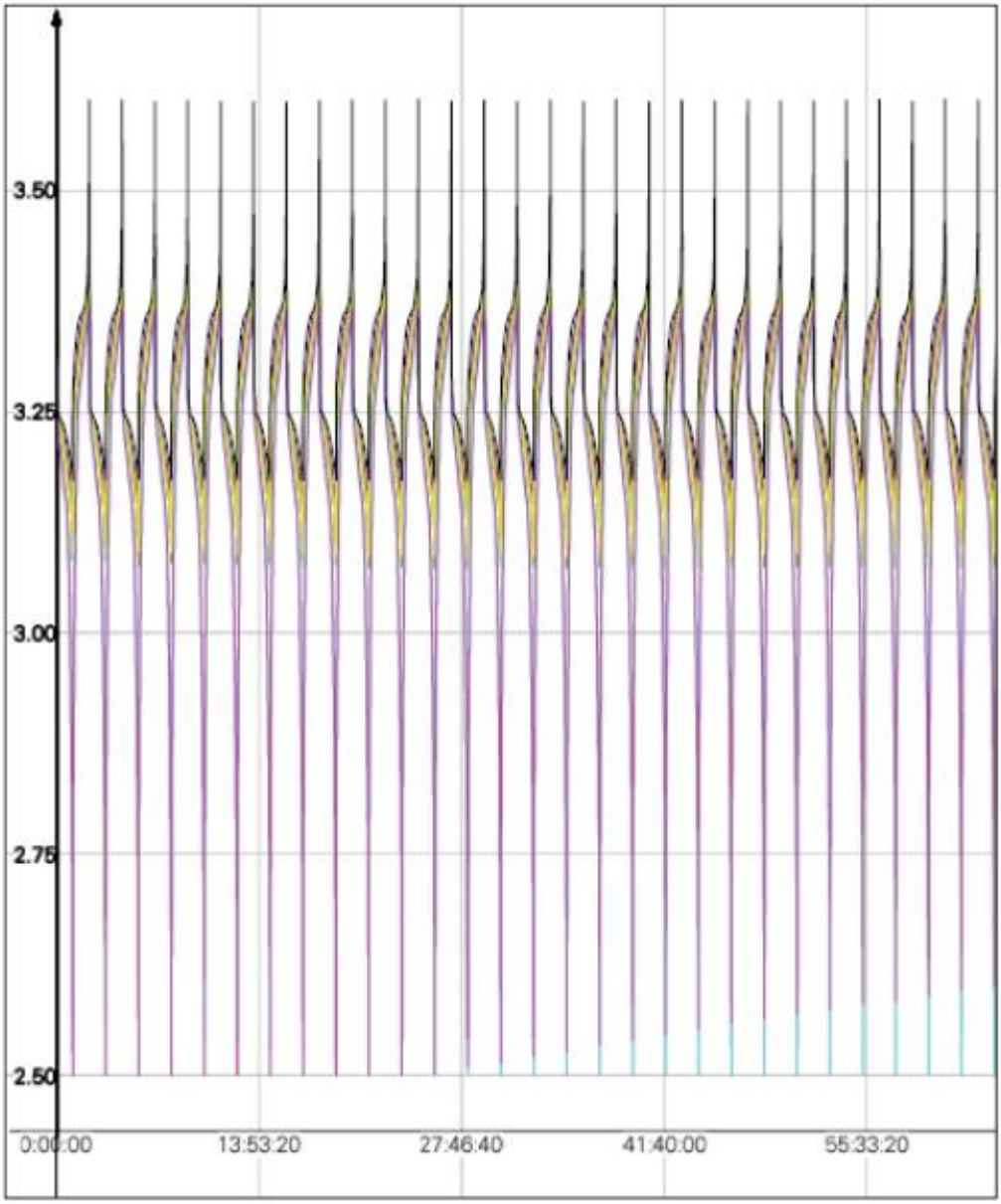


Figure D-9: Cell voltage curve during cyclization

The characterization and cyclization of the cells in **AS D.1** has shown that the battery cells within a system vary with regard to the parameters of internal resistance, capacity and state of charge. This has a significant impact on system performance during cyclization. These results are taken into account in **AS A.4.4** and an option for determining the cell parameters on a single-cell basis is included.

The performance of standard cell active material (NMC layered oxide) was recorded in so-called pouch full cells. These contain a cathode with a total active material area of 50 x 50 mm. A graphite electrode was used as the anode in each case.

with a size of 55 x 55 mm is used. The surface weight of the cathode was about 15 mg/cm^2 in each experiment. If the basis weight differs significantly from this value for some electrodes, the value for the corresponding test is given.

The test procedure for recording the performance consisted of a forming cycle (0.1C charging/0.3C discharging) and a subsequent C-rate test in which the C-rate was gradually

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

increased up to 10C. The exact sequence can be seen in Figure D-12. After this C-rate test, 475 cycles with 1C or 3C were performed to investigate the long-term stability of the cells. This long-term study was performed at three different temperatures (room temperature, 35°C and 45°C). The results are shown in Figure D-10 and Figure D-11. This clearly shows that at a charge rate of 1C, a temperature of 35°C causes the best cycle stability and a temperature of 45°C the worst. If the charging rate is 3C, the temperature of 21°C is best for long-term stability and 45°C ambient temperature shows the worst stability. In general, 3C as a charging rate causes significantly poorer performance than 1C.

The performance test shows a very different behavior of the cells at the individual temperatures, depending on how high the discharge current is. Up to a discharge current of 3C, 45°C ambient temperature is the least favorable for performance. For discharge currents with 5C or 10C, however, 35°C is significantly worse for performance than 45°C. However, the following applies consistently for all discharge rates: 21°C ambient temperature

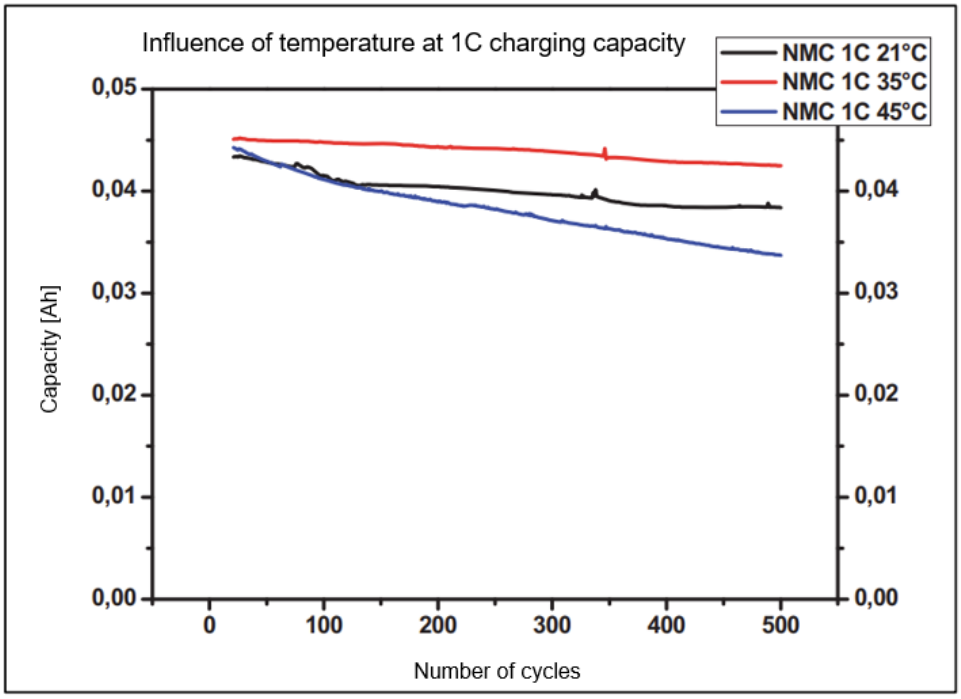


Figure D-10: Performance of standard layered oxide cells at 1C charge rate

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

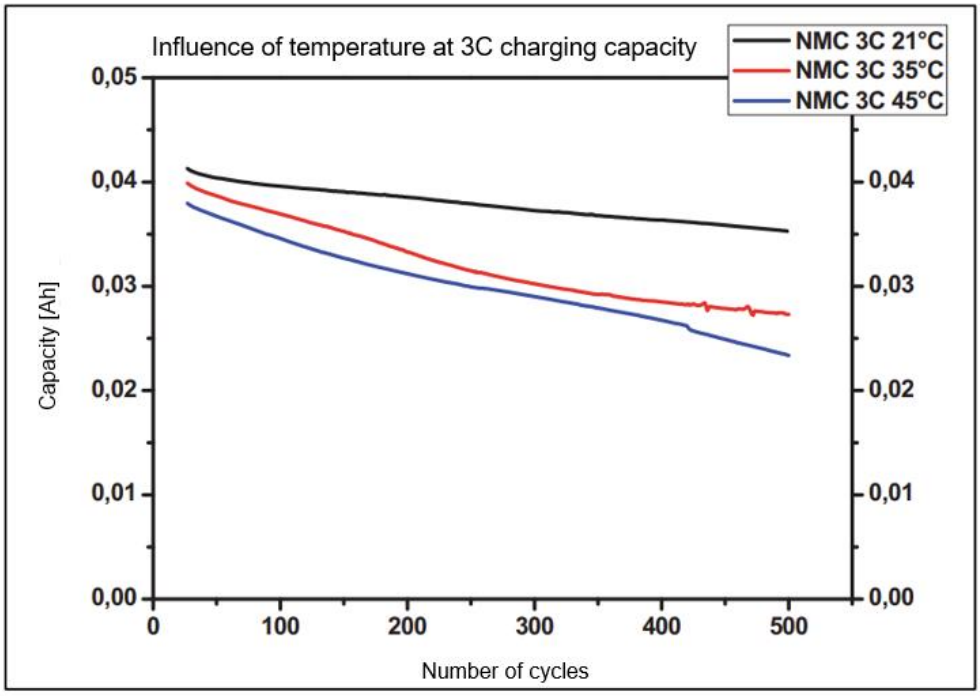


Figure D-11: Performance of standard layered oxide cells at 3C charge rate

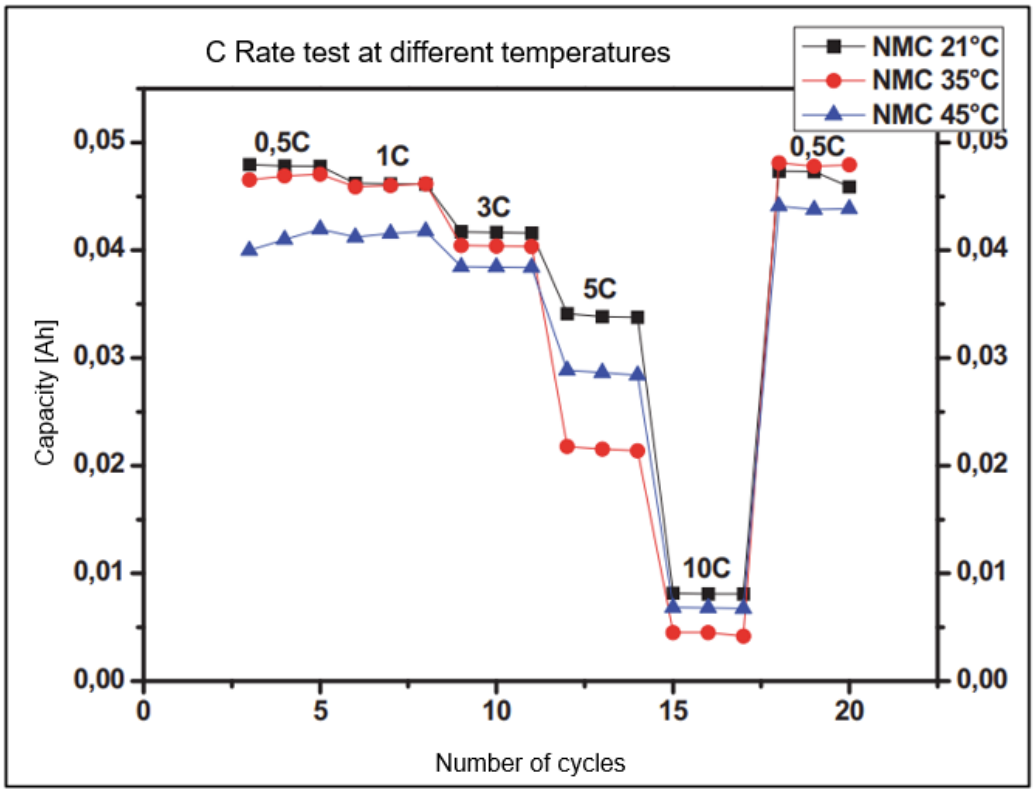


Figure D-12: C rate test at different temperatures

After cycling, post-mortem analyses were performed on the aged cathodes. This included adhesion tests to investigate the bonding mechanisms between the coating and the substrate film. The results are shown in Figure D-13. The adhesive force of the electrodes before cycling (standard, green) and the adhesive force of the cells after 1C or 3C charging rates and 21°C or

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

45°C ambient temperature are shown. The values shown consist of the mean values of ten measurements each. For the cyclized electrodes, five measurements were taken per electrode and two electrodes were evaluated.

As a result, it can be seen here that the adhesive force of the cathodes with a charging current of 1C is indistinguishable from the adhesive force of the originally manufactured cathode. Although the mean values differ slightly (the aged cathodes show a slightly higher adhesive force), but the standard deviation is so large that a meaningful statement is not possible here. The adhesive force of the cycled electrodes differed massively, which indicates that the binder within the electrode is affected to varying degrees and therefore also indicates uneven ageing behavior within the cell. This non-uniformity of the adhesive force is much more pronounced in cells that have been cycled at 45°C than in cells with a lower cycling temperature.
A charging current of 3C significantly reduces the adhesive force of the cathode layer on the aluminum substrate to 68% (21°C) or 83% (45°C) of the original value. It can again be observed that a higher temperature causes a greater dispersion of the values and thus a significantly higher standard deviation. In all these electrodes, the adhesion failure occurs within the particle layer. Only occasionally could it be observed that a partial adhesion failure occurred between the particle layer and the aluminum substrate. This phenomenon occurred regardless of temperature and charging current.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

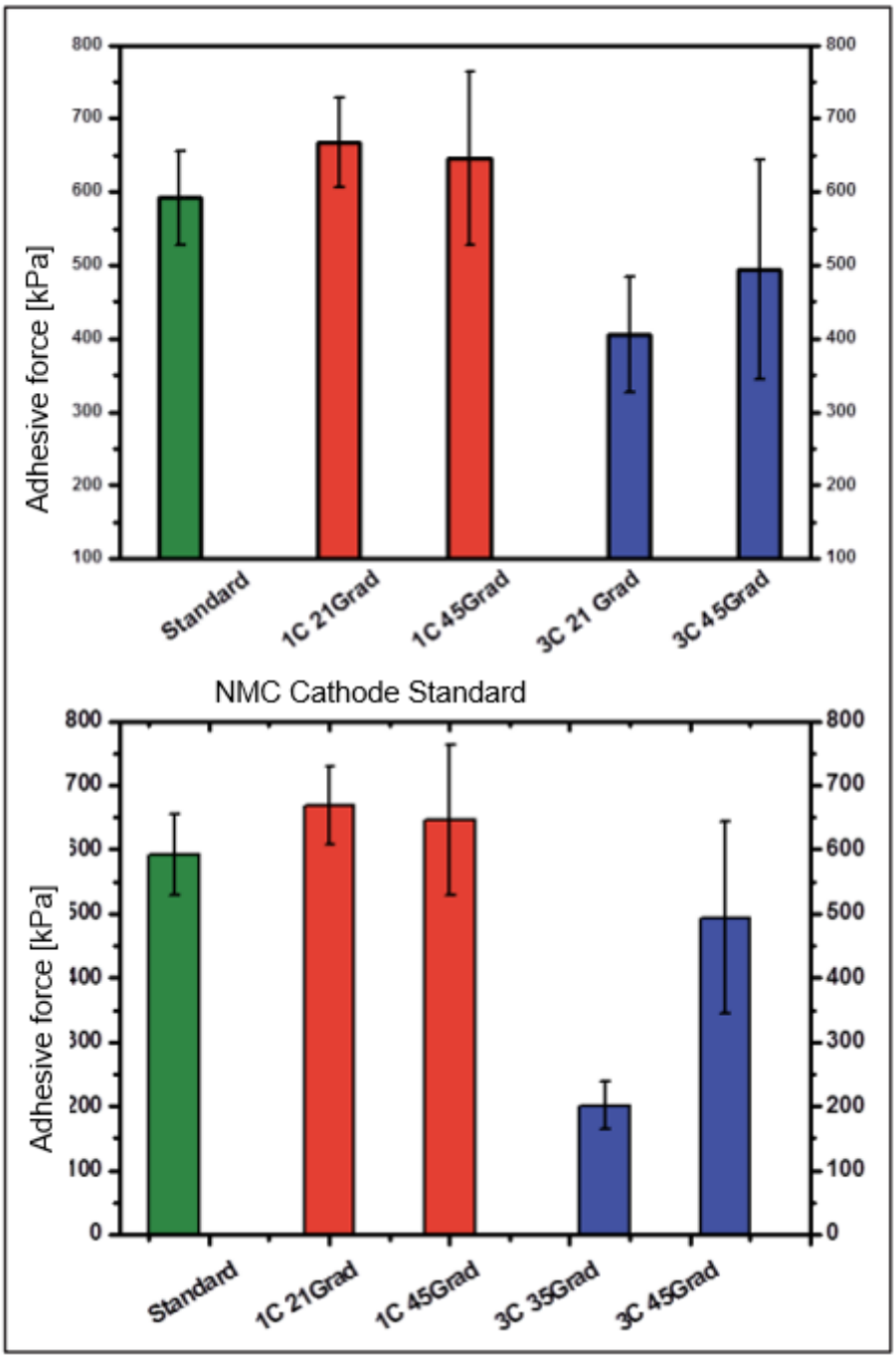


Figure D-13: Adhesive force measurement on cyclized cells (standard)

In nanoindentation measurement, an indentation tip is pressed into the surface of the electrode until a predefined force is reached. The distance traveled is recorded. Once the set maximum force has been reached, the needle moves back again. The force with which the elastic part of the layer presses against the needle is recorded. This allows the plastic and elastic parts of the deformation work to be recorded and the mechanical properties of the layer to be characterized.

The maximum set force was 8,000 µN. This value has proven to be very useful in previous experiments. The tip of the indentation needle is a flat circle (flat punch) with a diameter of 50 µm. To record the measured values, 30 individual indents were made at two different points on the electrode.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure D-14 shows the plastic, elastic and total deformation work when the indent penetrates the electrode.

A higher temperature (45°C) significantly reduces the proportion of elastic deformation work in the total deformation work. This behavior is independent of the charging rate and occurs at a current of 1C as well as at a current of 3C. A higher loading rate reduces the overall deformation work. The plastic and elastic parts become significantly smaller. At a temperature of 45°C, the elastic deformation work is hardly reduced when the charging current is increased from 1C to 3C. The influence of temperature on the elastic deformation work is significantly greater than an increase in charging current.

A reduced elastic deformation work after 500 cycles indicates a changed behavior of the binder. This loses some of its ability to compensate for the voltages within the electrode composite due to the long cycling.

This behavior is consistent with the electron micrographs taken of the cathodes before and after cyclization (see Figure D-15). At high charging rates (3C) and high temperatures (45°C), significantly more destroyed particles can be found on the electrode. This can be seen very clearly in Figure D-15 3a) and 3b). Some of the spherical particles are covered with cracks or completely split. Stress within the particles during cyclization and stress between the particles that is not transferred to the binder is the reason for the destroyed particles.

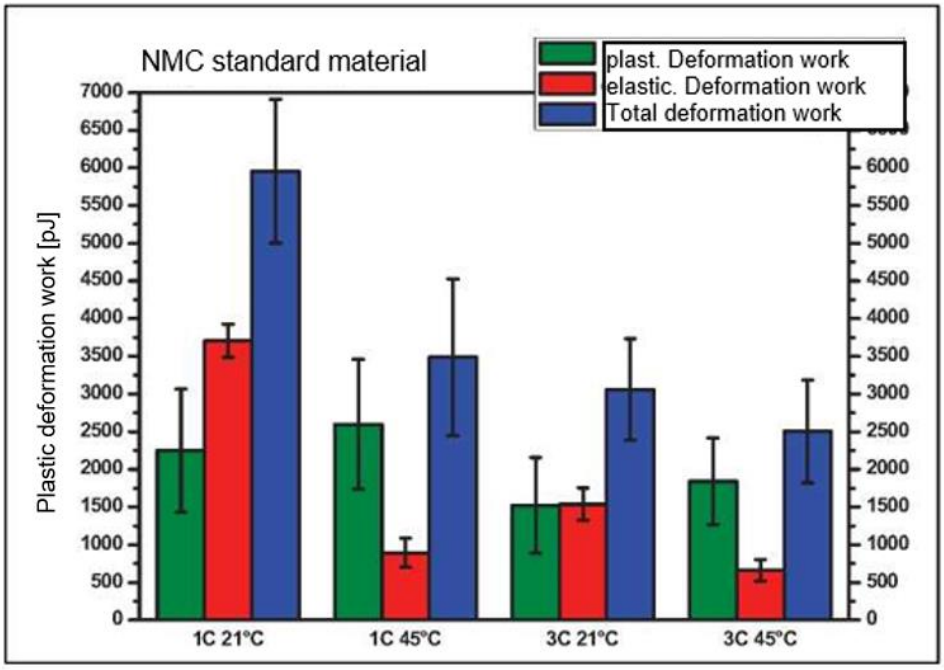


Figure D-14: Nanoindentation measurements on NMC standard material

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

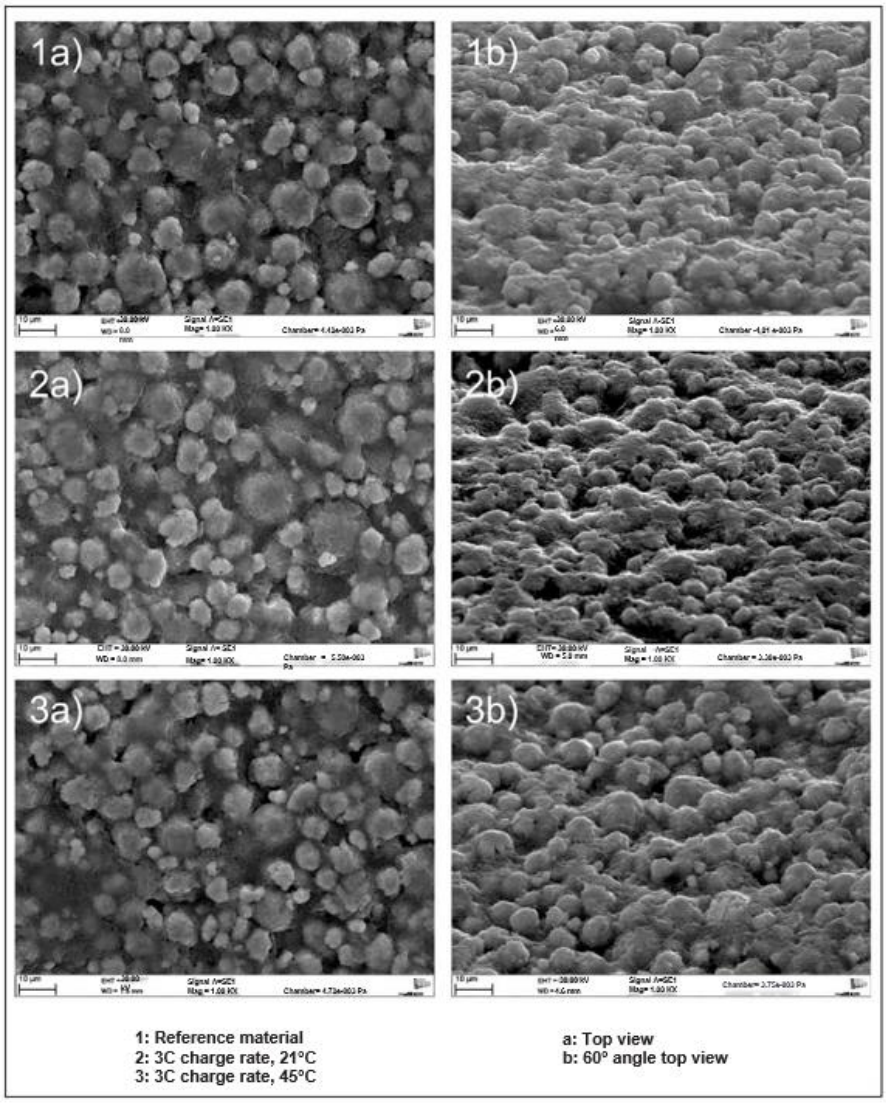


Figure D-15: SEM images of NMC standard material

D.2 Recording the performance and analyzing the aging of recycled active materials and multiple recycled active materials using a standard cell (LiFePO4 and layered oxides)

Due to the lack of recycled active materials, no practical tests could be performed. Furthermore, the samples cannot be processed by the LTR and CM due to their carcinogenic classification. The remaining characterizations are therefore only performed by IPC-WWU. The samples were delivered in August, so characterization is still ongoing.

The cells of one of the battery systems dismantled in the project were classified and are being cycled on a test stand at HTEE-TUBS. Used battery cells are therefore examined instead of cells made from recycled active materials. This is intended to provide a basis for evaluating the use of the returning systems in the fields of application identified in **AP A.4**. First, the cells were evaluated using the open-circuit voltage, analogous to the evaluation methodology developed in **AP A.4**.

The modules with the highest and lowest open-circuit voltages and the largest and smallest

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

difference in cell voltages were then selected and their performance tested on the HTEE-TUBS test stand.

The electrodes and cells produced in **AS C.3.3** and **AS C.3.4** were examined in this step for their performance at different charging/discharging currents and their aging behavior at different ambient temperatures.

The current load tests already mentioned in steps **AS C.3.3** and **AS C.3.4** were performed in this package at two different temperatures. (see Figure D-16 and Figure D-17). It was found that the difference in capacity between the reference material and the slightly and heavily contaminated materials increased significantly at a significantly higher temperature (45° C). The difference between the capacities of the cells at 21° C and 45° C is explained by the different surface mass.

At a temperature of 21° C, there is hardly any difference between the reference and the material V21, as already described in **AS C.3.3**. The active material with the higher impurities (V5-Z) shows a 15-20% lower capacity. A charge/discharge current of 10C causes a capacity of about 10% of the original value. However, this waste is identical for all three materials examined. Subsequent cycling with a charging rate of 0.5C, however, allows the capacity to return to the initial value. This drop at the start of ageing does not leave any irreversible damage visible in the capacitance.

At an ambient temperature of 45°C, a clear difference can be seen between the three materials. The reference material shows the best performance at all charging currents. The material V21 with the light impurities has a capacity that is approx. 10% lower than the reference material. Only at a charging rate of 10C is this difference no longer noticeable. Here, the drop in material V21 is not as sharp as the drop in the reference. The heavily contaminated material V5-Z shows the lowest capacitance compared to the reference or material V21. After the load test with up to 10C, the cells were charged and discharged 3 times with 0.5C. As with the temperature of 21°C, this showed that the high current rates did not cause any recognizable physical damage.

The results of the cycle stability at the two different temperatures and a charge rate of 3C are shown in Figure D-18 and Figure D-19. At both temperatures, it is clear to see that the heavily contaminated material V5-Z shows the weakest performance.

At 21°C, the capacity of the cell drops to approx. 2/3 of the original capacity within the first 50 cycles, then stabilizes at this value and loses only very little capacity in the last 400 cycles. The slightly contaminated material V21 shows the best long-term stability in this test, also in comparison to the reference material. If the temperature rises to 45°C, the cells with the V5-Z active material show the worst performance. The behavior of the reference material and material V21 is almost identical. Although the drop in capacitance of the reference is initially significantly greater than that of the material V21, this loss stabilizes at cycle 200 and from this point onwards the performance of the two materials is almost identical.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

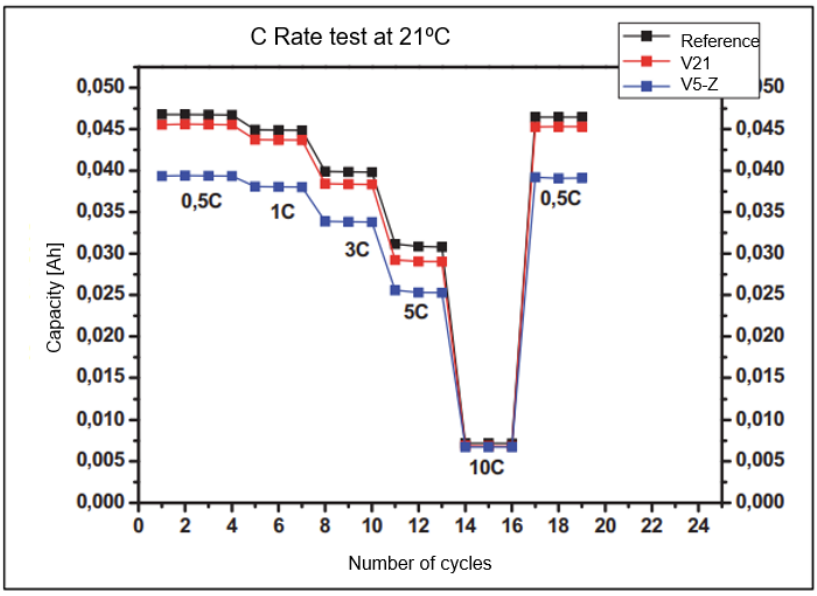


Figure D-16: C rate test NMC at 21°C

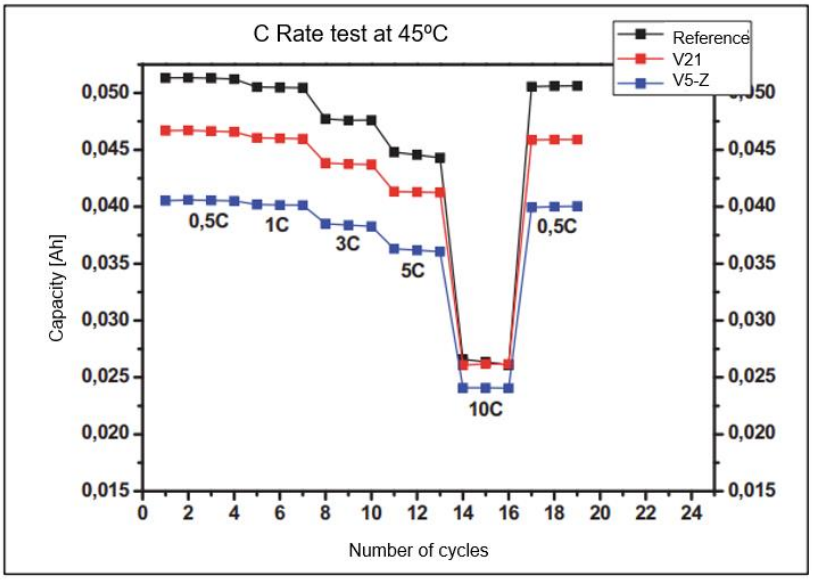


Figure D-17: C rate test NMC at 45°C

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

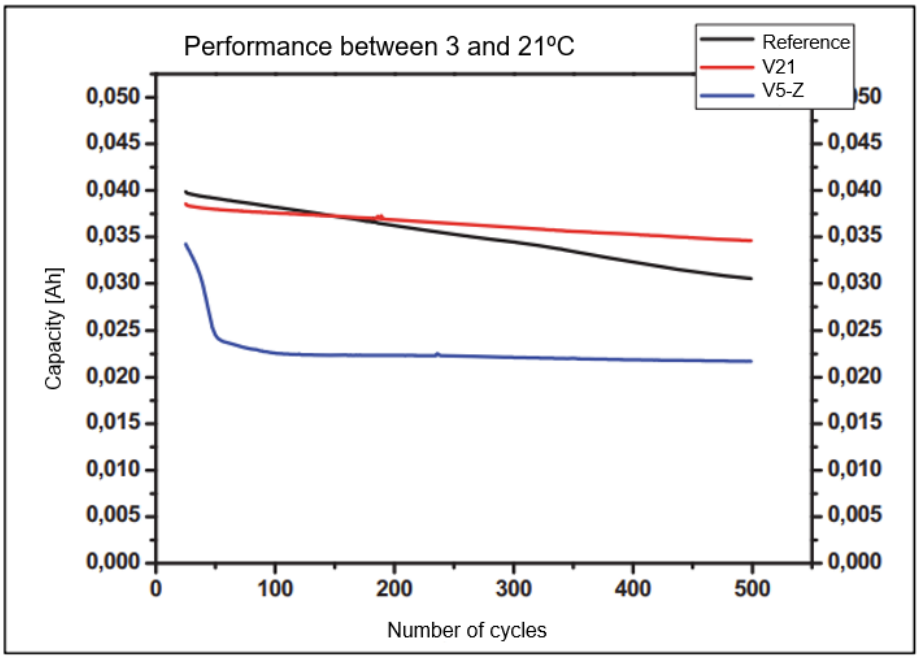


Figure D-18: Performance NMC at 21°C and 3C

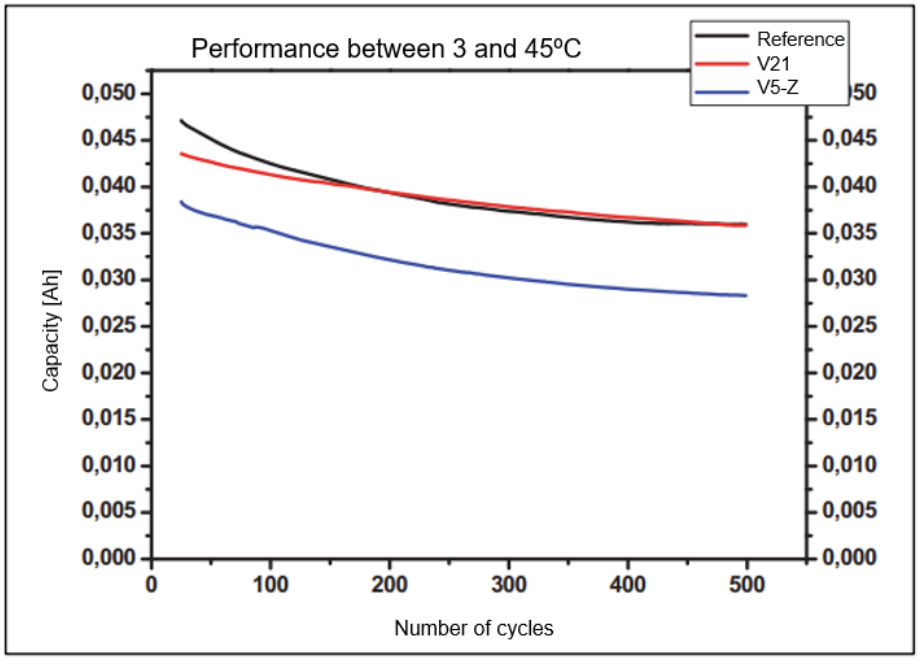


Figure D-19: Performance test NMC at 45°C and 3C

A post-mortem analysis was performed on these cells, analogous to **AS D.1**. The results of the adhesive force test are shown in Figure D-20. Cyclization significantly reduces the adhesive strength of the coating. However, temperature also has a negative influence on the adhesive force. The type of adhesion failure also changes. While the uncycled electrodes show a failure of the adhesive force within the particle composite and the layer of particles is torn apart during the pull-off test, the entire particle layer of the cyclized electrodes tears off completely from the aluminium foil. This behavior is all the stronger the more contaminated the active materials are. The material V5-Z shows the lowest adhesive force between the particle layer and the aluminum substrate. It can be observed that the aluminum foil has become significantly duller, which indicates a reaction of the aluminum foil with the electrolyte during cycling.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

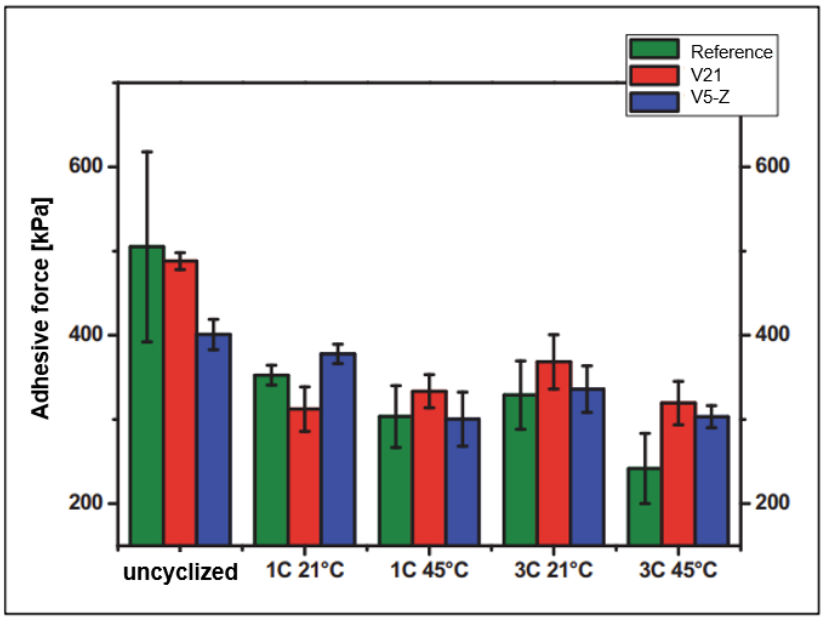
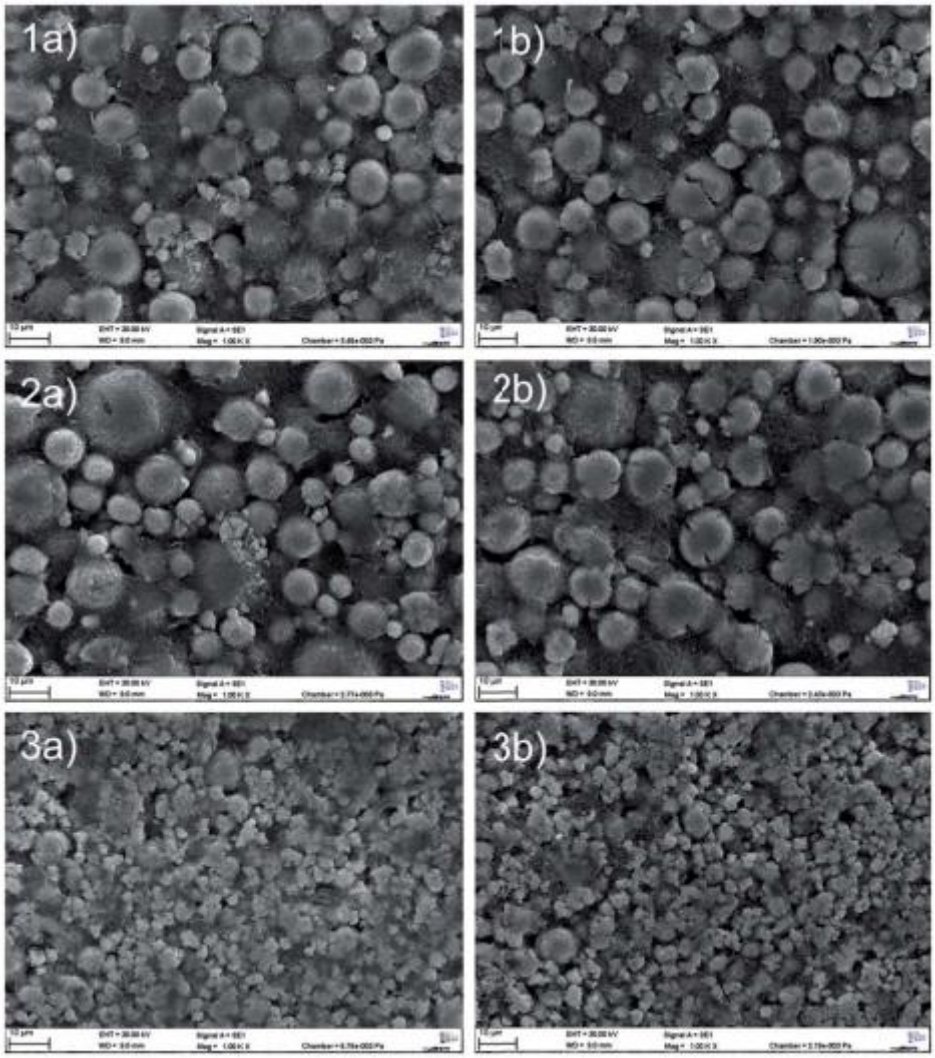


Figure D-20: Adhesive strength test of NMC material at different loading rates and temperatures

The impurities that occur in the recycled active materials have no influence on the adhesive force of the particles to each other or on the adhesive force between the particles and the substrate film. The different morphology of the particles of the materials V21 and V5-Z does not measurably affect the adhesive force. Only the type of adhesive force failure changes, as described above.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.



1: Reference material **a: 21°C**
2: Material V21 **b: 45°C**
3: Material V5-Z

Figure D-21: SEM images of NMC recycling material at 1C charge rate

The images from the electron microscope (SEM) (Figure D-21) show that some of the particles break up during cyclization. This behavior was already observed in **AS D.1** with the standard material. The reference material in **AS D.2** shows a similar behavior. Here too, the number of defective particles increases with a higher charge rate and higher temperature.

Material V21 shows similar behavior to the reference material, but the number of destroyed particles is significantly greater. (see Figure D-21 2b)). Unfortunately, it was not possible to determine whether defects also occur in the particles of material V5-Z. These electrodes consist of large agglomerate structures and cracks cannot be distinguished from the boundaries of the primary particles.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

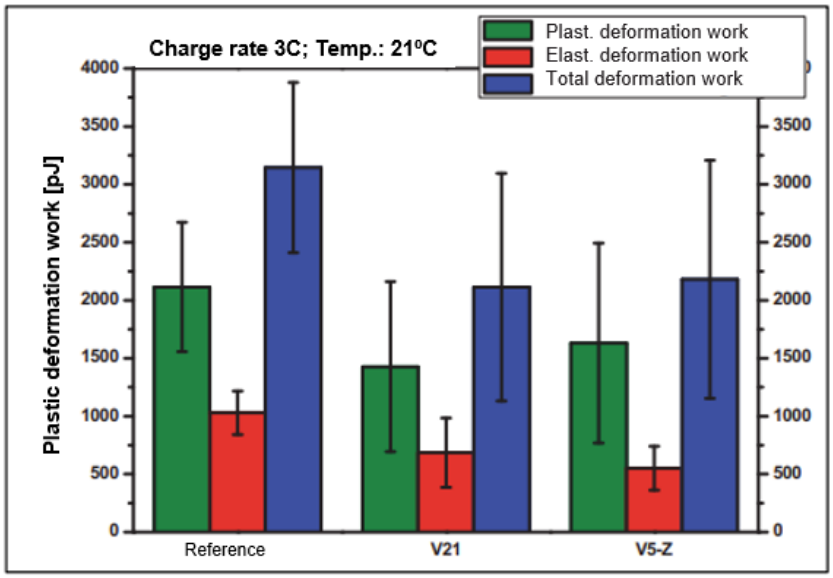


Figure D-22: Nanoindentation of recycled material. Charge rate 3C, temperature 21°C

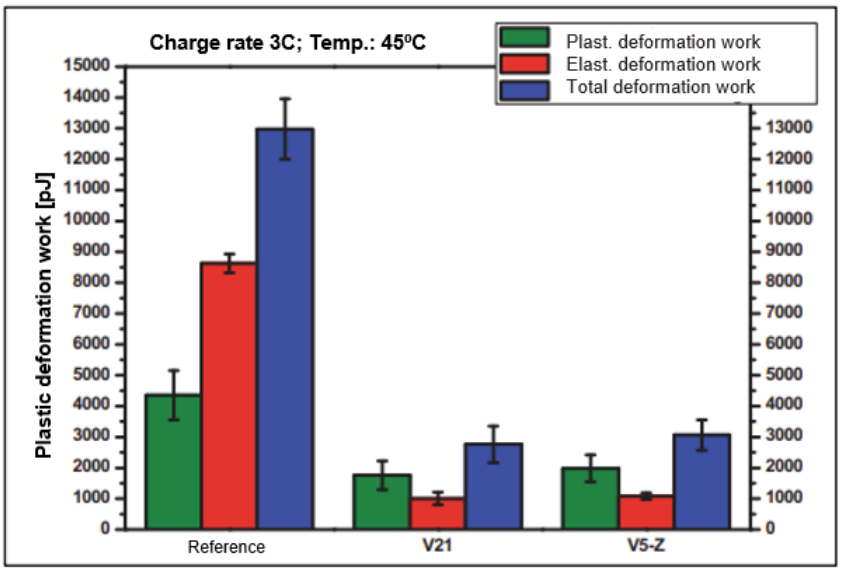


Figure D-23: Nanoindentation of recycled material. Charging rate 3C, temperature 45°C

The nanoindentation tests on the recycled materials V21 and V5-Z, as well as the reference material, are shown in Figure D-22 and Figure D-23. It can be clearly seen that the impurities in the materials V21 and V5-Z significantly reduce the proportion of elastic work. This indicates a strong influence of these impurities on the binder. This thesis is also supported by the electron microscope images. The images of the materials V21 and V5-Z show a changed binder structure after cyclization. While the binder is bound around the particles as a homogeneous structure in the uncyclized material and the reference material after cyclization, a changed structure of the binder can be seen in the images of the cyclized contaminated materials. In the photos, it looks as if parts of the binder material have been detached. The structure resembles etched metal. The higher the temperature and the higher the charging rates, the greater the change in the binder.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

D.3 Analysis of the mechanisms of ageing in comparison of conventional and recycled active materials

Due to the lack of recycled active materials, no practical tests could be performed. Furthermore, the samples cannot be processed by LTA and CM due to their carcinogenic classification. The remaining characterizations are therefore only performed by IPC-WWU. The samples were delivered in August, so characterization is still ongoing.

The influences of the ageing mechanisms on the mechanical properties of the cells after cycling lead to the same changes. With conventional material, as with recycled material, the adhesive force between the particles and between the particles and the substrate film is significantly reduced. However, it must be differentiated here that the recycled material from cells that have already been cycled (V5-Z) exhibits a significantly reduced adhesive force to the substrate film, while the cells made from reference material and recycled material from rejects (V21) exhibit a failure of adhesion within the particle composite. This behavior indicates a reaction of the materials with the aluminum substrate foil, which remain in the active material during recycling. This reaction changes the binder and significantly reduces its adhesive properties.

A reaction of the binder with the substances from the recycling process can also be deduced from the nanoindentation studies. Both recycled materials (V21 & V5-Z) show significantly less elastic behavior than the reference material. The binder has therefore significantly reduced its elastic properties after cyclization. A high temperature (45°C) during cycling significantly increases this effect, whereas a significantly increased charging rate (3C compared to 1C) has hardly any influence.

Furthermore, an increased breaking of the particles can be observed. This behavior is hardly observed with the conventional material in **AS D.1**, while the material V21 in **AS D.2** has a high number of defective particles. The number of broken particles is strongly dependent on the charge rate and temperature. The higher the charge rate and temperature, the more frequently broken particles occur.

E Economic and ecological evaluation of recycling concepts for Li-ion batteries

The aim of **PB E** is the economic and ecological evaluation of the recycling processes conceptualized and developed in *LithoRec* as well as the assessment of the contribution of recycling to the availability of important battery raw materials.

E.1 Survey and process simulation of energy demand

In **AS E.1**, HTEE-TUBS quantifies how the process selection in **AP A.4** affects the energy demand of the entire process. It is assumed that the following typical battery capacities are used.

Table E-1: Typical capacities of automotive battery systems

DIN EN 61982-3 describes general requirements and the testing of the service life of secondary batteries for the propulsion of road vehicles. It is assumed that at the end of the service life of a

	BEV battery	PHEV battery	HEV battery
Battery capacity per battery in [kWh]	23.1	9	1

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

secondary battery, the battery capacity is 80% and that the battery systems are delivered with a state of charge of 50% of their current capacity. The following energy contents per battery result from the assumed data:

- For Batteries with BEV: $23\,\frac{\text{kWh}}{\text{Battery}} \cdot 0{,}8 \cdot 0{,}5 \approx 9{,}2\,\frac{\text{kWh}}{\text{Battery}}$ (5.1)

- For Batteries with PHEV: $12{,}1\,\frac{\text{kWh}}{\text{Battery}} \cdot 0{,}8 \cdot 0{,}5 \approx 4{,}84\,\frac{\text{kWh}}{\text{Battery}}$und (5.2)

- For Batteries with HEV: $1{,}3)\,\frac{kWh}{Battery} \cdot 0{,}8 \cdot 0{,}5 \approx 0{,}52\,\frac{kWh}{Battery}$ (5.3)

The expected energy content can thus be determined from the expected return rates of the battery systems determined in **PB A**. Figure E-1 shows the expected energy content of the BEV battery systems over time. A significant share can only be expected with a significant increase in returning battery systems.

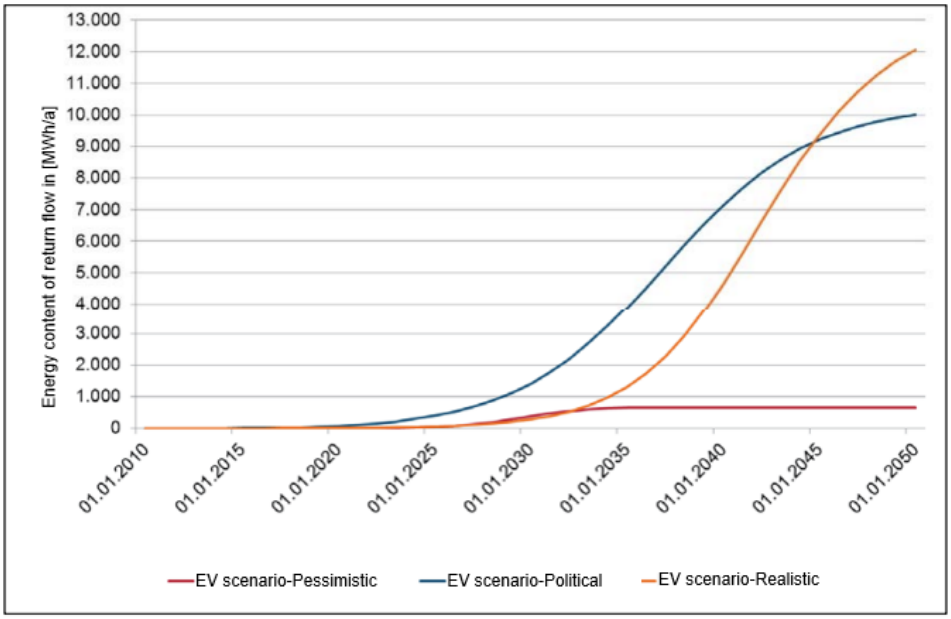


Figure E-1: Energy content of the returning battery systems

These results were transferred to **AP A.4** and used there to decide on the type of discharge for the battery systems. For the utilization of the residual energy of the returns, it is also important whether the energy must be used locally or fed back into the electrical supply grid. When feeding energy back into the public grid, the grid connection conditions in particular must be complied with and contractual provisions for the remuneration of the energy fed back must be negotiated. If the electrical energy is consumed locally, feeding it back into the grid is simplified and revenue is generated by reducing the amount of electricity purchased.

For the recycling process chain, the electrical energy consumption that occurs at the place of possible discharge was therefore taken into account and determined in accordance with Table E-2.

Table E-2: Determined energy consumption

Electrical energy consumption	
Transportation	20 —
System dismantling	0.3 —

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Electrical energy consumption	
Module dismantling	0.15 —
Electrode separation	50 —

The further processing of the separated electrodes was not used for comparison with the electrical energy quantity of the returned electrodes, as further processing is currently performed at a separate site and the separated electrodes are transported there.

The electrical energy consumption of electrode separation dominates this part of the treatment process. Utilization of the residual electrical energy in the returning battery systems can reduce electrical energy consumption by approx. 20%.

E.2 Life cycle assessment of the entire recycling process chain

In **AS E.2**, the Öko-Institut Darmstadt was supported in defining the target and investigation framework and in collecting data for the life cycle assessment of the recycling process and was assisted in the preparation of the study by discussing product-, process-related and methodological issues (e.g. with regard to allocations, credits, assessment methods). The results of the life cycle assessment have been published in a comprehensive separate report by the Öko-Institut and the Umbrella Group LCA.[16]

E.3 Development of a material flow model for cobalt and lithium, availability study

The results of the Umbrella Group “Resource Availability” have been published in a comprehensive separate report.[17]

E.4 - E.6 Economic evaluation of the LithoRec process

Various alternatives for recycling traction batteries were developed in the course of the project. The work steps **AS E.4** to **AS E.6** pursued the goal of identifying advantageous alternatives while taking potential restrictions into account and are considered here in an integrated manner.

In addition to and in close cooperation with the investigations in **PB E**, the AIP-TUBS has examined various process paths from a production management perspective. Some of the technical process routes examined were excluded for technical reasons, others for economic reasons for a more detailed economic analysis. Figure E-2 shows the process paths envisaged in the course of the project. Basically, the process from removing the battery from the vehicle to synthesizing new active material for the production of new cells can be divided into seven steps: Battery removal (1), battery system dismantling down to battery module level (2), battery module dismantling down to cell level (3), cell dismantling (4), electrode separation (5), hydrometallurgical processing of the active material (6) and active material synthesis (7). Steps 1 and 7 were excluded from the analysis and are therefore outside the system limits. Steps 2 and 3 have been combined in the illustration for practical reasons. Steps that could in principle be performed using alternative procedures are marked

[16] See Buchert et al. (2011).
[17] See Konietzko and Gernuks (2011).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

alphabetically. The main technical alternatives here are to disassemble the cells and separate the cathodes.

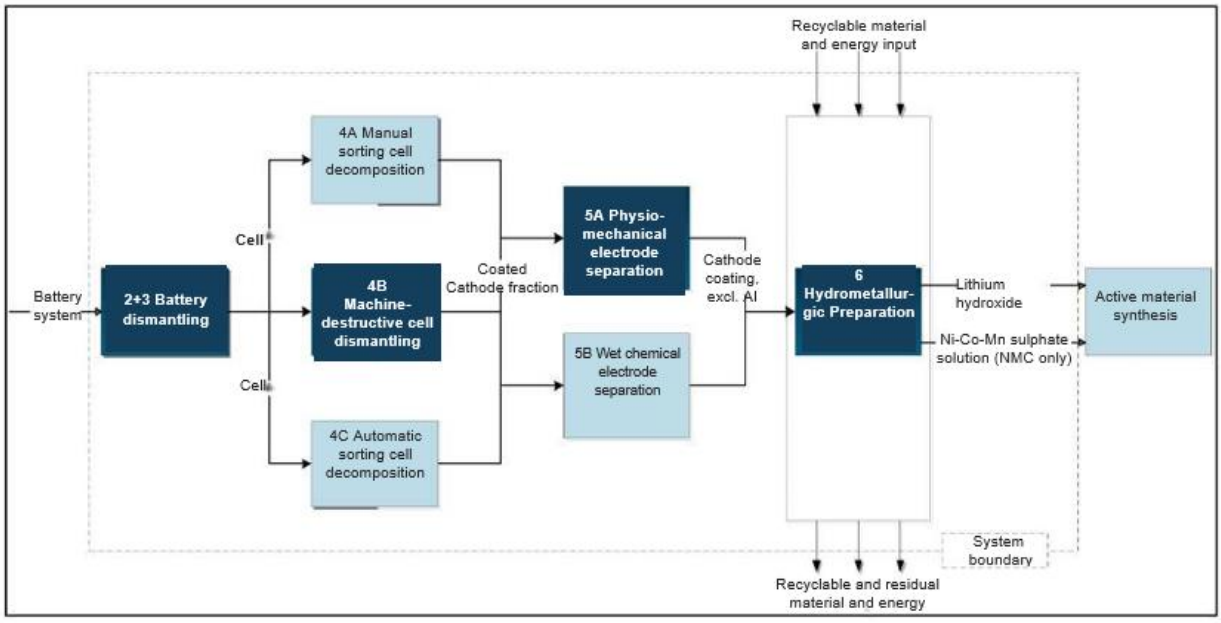


Figure E-2: LithoRec process chain with alternative process paths

With regard to cell dismantling, manual sorting (4A) and automatic sorting cell dismantling (4C) were excluded from the economic evaluation and process design. Manual sorting separation was ruled out due to the high effort involved and the considerable risks for employees due to direct cell contact (e.g. cuts, short circuits, deflagration, chemical burns, etc.).[18] The automatic sorting cell decomposition was excluded as it could not be technically investigated further within the project.

With regard to electrode separation, wet-chemical separation (5B) was excluded, as it appears to be inferior to physio-mechanical electrode separation from a technical, economic and ecological point of view: on the one hand, a significantly lower recycling efficiency is achieved. On the other hand, large quantities of ecologically questionable solvents have to be used, for which no possibility of recycling could be investigated during the project period.

After excluding the alternatives, one possible process path remains, which includes mechanically destructive the cells using a shredding process and physio-mechanical electrode separation. This was initially examined technically and ecologically in the course of the project and is evaluated economically below. The following procedure has been adopted for this evaluation in close cooperation and coordination with partners from the **PB A** and **PB B** project areas:

1) **Modularization** of the logistical and production-related *LithoRec* processes and Creation of **reference installations** (Section E.4.1)
    - **Investment estimate** for the **reference plants** of different capacities and estimate of **plant-related fixed costs** (section E.4.2), plus estimate of investment-dependent costs and operating costs independent of capacity utilization.
2) Estimate of battery type and **system-dependen**t contribution margins for NMC and LFP batteries (section E.4.3), including estimate of material flow revenues and costs from the individual processes based on the material and energy balance from E.1 and E.2 and estimate of process

[18] In order to process one BEV system per hour, 45 employees have to work on one glove box at a time. With an estimated unit price of EUR 3.500, this would mean EUR 157.500 for glove boxes. In addition, the variable costs are at least EUR 675 for separating the cells of a system.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

costs for the treatment of batteries, cells and active material

3) **Break-even analysis** based on the calculated fixed costs and contribution margins for each of the facilities under consideration, excluding the transshipment facility (E.4.4)

E.4.1 Modularization and creation of reference systems

In order to estimate plant investments, individual process steps of the LithoRec process chain were first analyzed with regard to their modularizability in terms of production technology and logistics. This was done under the following conditions:

- The evaluation of process steps that can be performed independently, e.g. the dismantling of batteries, should be performed independently of subsequent process steps that are not absolutely necessary, e.g. the hydrometallurgical treatment of the active material.
- The summary of process steps should be in line with the technical investigations in project areas **PB B** and **PB G** and reflect the concepts developed there.
- The spatial decoupling of process steps should be taken into account so that the results of the evaluation can be incorporated as directly as possible into the evaluation of logistical networks in work package **AP A.3**.

Accordingly, the processes were modularized as follows:

Logistical collection processes: (transshipment) warehouse for used lithium-ion traction batteries

Used batteries are stored in transshipment warehouses after collection and until they are transported onwards (e.g. to dismantling plants). The investment and cost estimate for transshipment warehouses serves exclusively to evaluate different logistical structures in AP A.3. In order to be able to evaluate economies of scale, the investments and costs were estimated for two differently dimensioned warehouses. **Small transshipment** warehouses offer space for the storage of 50 BEV equivalents.[19] Assuming a maximum handling frequency of 200 handling operations per year, this corresponds to a maximum handling capacity of 10,000 BEV equivalents. **Large transshipment** warehouses offer space to store ten times the quantity (500 BEV equivalents) and a maximum transshipment capacity of 100,000 BEV equivalents. Irrespective of the specific institutional organization (cross-manufacturer or manufacturer-specific, independent or networked), the depots should be able to autonomously collect waste batteries in a part of the territory of the Federal Republic of Germany.

Process steps 2+3: Dismantling plant for used lithium-ion traction batteries

In dismantling plants, the old battery systems are largely discharged and dismantled down to cell level after being stored for a short time if necessary. The cells are then discharged again to a voltage of 0 V. with the exception of the cells, the individual fractions (e.g. steel and plastic housings, copper cables, BMS) either find their way into the existing recycling structures or have to be disposed of. The cells are then transported for further processing. The investments and costs were estimated for two differently dimensioned dismantling plants. The **small dismantling plant** is designed to process at least 5,000 BEV equivalents or 1.600 tonnes of systems per year (three-shift system, 250 operating days, 20 units per day). By extending the operating time to 300 operating days, the annual throughput could be increased to 6,000 BEV equivalents.[20] The large **dismantling plant** is designed to process ten times the amount of at least 50,000 BEV equivalents or 16,000 tonnes of systems per

[19] For an explanation of BEV equivalents, see report on AP A.3. An HEV battery is assumed to correspond to 1/10 BEV equivalents, a PHEV battery to% BEV equivalents.

[20] The actual capacity depends on the specific operational design and may be lower or higher accordingly. The specified values are to be understood as guide values.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

year (200 units per day, 60,000 BEV equivalents with 300 operating days per year).

Process steps 4B+5A: Mechanical processing of active materials from lithium-ion cells

In mechanical processing plants, cells sorted according to LFP and NMC active material are first destroyed ("shredded") by machine. The fractions are then roughly sorted and in some cases further processed. The separation of the mixed cathode fraction is physio-mechanical and the recovered cathode coating can then be transported for hydrometallurgical processing. Other recyclable and residual materials are disposed of in existing waste and recycling structures. The investments and costs were estimated for two differently dimensioned treatment plants. **Small mechanical processing plants** are designed for an annual throughput of 1,000 to 1.500 tonnes of cells (approx. 5,000 to 7.500 BEV equivalents/year or 1.600 t to 2.500 t systems). This corresponds to an hourly cell throughput of 170 kg. **Large mechanical processing plants** process ten times the amount of 10,000 to 15,000 tonnes of cells per year (approx. 50,000 to 75,000 BEV equivalents/year or 16,000 to 25,000 tonnes of systems). The hourly cell throughput is approx. 1.700 kg.

Process step 6: Hydrometallurgical processing of active materials

In hydrometallurgical processing plants, the cathode coating, which was previously recovered in mechanical processing plants, is processed hydrometallurgically. This is done with the aim of recovering lithium in the form of high-purity lithium hydroxide monohydrate ($LiOH - H_2O$) or lithium carbonate (Li_2CO_3) and, if necessary, the solution containing cobalt and nickel. The plant under consideration corresponds to the Chemetall pilot plant, whose investment sum is known. The annual processing capacity of the already completed plant depends on the specific operational design. It is estimated by Chemetall to be the equivalent of 30,000 to 50,000 BEV equivalents (10,000 to 16.500 tonnes of systems) or around 700 to 1.150 tonnes of lithium hydroxide monohydrate.

E.4.2 Estimate of investments and fixed costs

Since, apart from the hydrometallurgical processing plant, there are no specific construction projects and therefore no construction plans for the reference plants on which the individual items could be determined, the investments and fixed costs associated with them must be roughly estimated. To this end, estimate methods are used below, the accuracy of which is limited due to the prevailing uncertainties. These methods are classified as summary methods and factor methods, which according to Peters, Timmerhaus et. al (2002) have an error range of 10 to over 30 percent. This means that the actual capital requirements of systems of a given specification are very likely to be within an interval of 10 to 30 percent above or below the estimated values. The investments and costs estimated below are based on these assumptions.

E.4.2.1 Transshipment warehouse

The **following procedure** was adopted for a rough estimate of the investment for the construction of transshipment warehouses:

- Calculation of the unit and area-related storage requirements for a given handling capacity with 200 handling operations per year and a space requirement of 4 Euro pallets per BEV equivalent.
- Determination of the required number of standardized storage racks, distinguishing between two different rack types with identical basic dimensions of 5.700 x 2.200 mm (width x depth):
    - Type 1: Storage on three levels, height 4.500 mm. Capacity: 12 BEV equivalents.
    - Type 2: Storage on four levels, height 6,000 mm. Capacity: 16 BEV equivalents.
- Estimate of the hall floor area and the specific building investment under the requirements and assumptions:

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- Storage aisle width 4400 mm, surcharge and rounding for shunting traffic and technical rooms.
- Sealed floor and buildings in fire-retardant construction.
- Area-related investment 800 EUR/sqm (usable height 5 m), 900 EUR/sqm (usable height 6.5 m).

- Estimate of the land area and the specific land investment under the requirements and assumptions:
  - Access areas, i.e. traffic, delivery and parking areas: 10 m width on the length of one side of the building when a square building is placed underneath.
  - Land-related investment (land purchase incl. fees and taxes) EUR 30/sqm.
- Specification of the need for battery-powered industrial trucks (warehouse forklifts) with a minimum payload of 1.5 t and a lifting height of at least 6 m (unit-related investment of EUR 30,000) and F90 safety containers for defective batteries (unit-related investment of EUR 35,000).

The estimate of the individual items and the total investment for a small and a large transshipment warehouse can be found in Annex 10. The **total investment for a small transshipment warehouse** is therefore estimated at **around** EUR 330,000, for a large transshipment warehouse at around EUR 1.5 million[21]. The sum could be up to 20 percent (small transshipment warehouse) or 15 percent (large transshipment warehouse) higher due to stricter requirements for the storage racks or the industrial trucks or due to higher land prices. The area-related building investment is already generously set and corresponds to a high building standard.

Annual investment-related costs can be divided into interest, depreciation, repair/maintenance, administration and insurance costs (Formula 1). Using specified specific technical useful lives and residual values[22], the annual imputed depreciation was calculated on the basis of the respective investments of the individual items.

Interest and depreciation costs are estimated (formula 2 and 3 respectively). It is assumed that the technical installations can be used for 20 years, while buildings can be used for 40 years. Annual costs for repair and maintenance were determined using specific maintenance rates, which represent an empirical proportion of the specific investment (Formula 4). Costs for investment-related administration and insurance were included as further investment-related costs (formulas 5 and 6). Imputed risk costs were neglected. As a result, the **annual investment-dependent cost**s for small transshipment warehouses are EUR 34,000/a, for large transshipment warehouses EUR 147,000/a (see Annex 11). The specific building investment has the greatest influence on costs (56 and 67 percent respectively).

$$K_{Invest} = K_{interest} + K_{depreciation} + K_{maintenance} + K_{administration} + K_{insurance} \qquad 1$$

with

$$K_{interest} = \sum_{t,i} \left(\frac{Specificinvestment_{i}}{2} + Residual\ value_{i} \right) * Zinssatz \qquad 2$$

[21] Due to the uncertain nature of the rough estimate, investments and costs are roughly rounded here and in the following explanations. The exact values are listed in the respective tables.
[22] Sales or scrap value at the end of the technical service life.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

$$K_{Depreciation_i} = \Sigma_t \frac{\text{Specificinvestment}_i - \text{Residual value}_i}{\text{Useful life}_i} \quad 3$$

$$K_{Maintenance} = \sum_i \Sigma_t \, SpecificInvestment_i * Maintenance\ rate_i \quad 4$$

$$K_{Management} = ManagementRate * Total\ investment \quad 5$$

$$K_{Management} = ManagementRate * Total\ investment \quad 6$$

In addition to the investment-dependent costs, the following **operating costs** were included in the annual costs independent of capacity utilization:

- Costs for management personnel: 15 percent surcharge on operating personnel costs.
- Ancillary operating costs (energy and cleaning costs, water, wastewater and refuse charges, property tax) of EUR 12/(sqm*a) in relation to the building area.
- Other overheads (mainly personnel administration): Surcharge of 15 percent on operating personnel costs.

Operating personnel costs were assumed to be variable due to the strategic approach and are therefore only included in the contribution margin calculation. However, they still had to be estimated in order to calculate the costs, which are charged as surcharges on the operating personnel costs. For this purpose, the number of warehouse specialists required to achieve the maximum target turnover was calculated and multiplied by the estimated gross employer salary of EUR 35,000 per year:

- Employees in the small transshipment warehouse in a three-shift system: 3, operating personnel costs: EUR 105,000/a.
- Employees in the large transshipment warehouse in a three-shift system: 12, operating personnel costs: EUR 420,000/a.

The annual **fixed costs** add up to around EUR 70,000 (small transshipment warehouse) or EUR 290,000 (large transshipment warehouse). The fixed costs can be divided into imputed costs and pagatoric costs (see Annex 12). The pagatoric costs can then be used for dynamic assessments, particularly in network planning in **AP A.3.** The pagatoric costs include the repair and maintenance costs, the investment-related costs for administration and insurance as well as the operating costs independent of capacity utilization.

The size degression exponent (GDE) can be used to quantify the economies of scale that occur with larger capacity plants. If there is a size de- gression, the fixed costs increase less than proportionally with the increase in capacity (the GDE is less than 1). The calculation is based on formula 7.

$$GDE = \frac{IN\left(\frac{Investment_{large}}{Investment_{Small}}\right)}{(In\left(\frac{Capacity_{large}}{Capacity_{Small}}\right)} \quad 7$$

The following classification is used to evaluate the size degression:

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

GDE < 0.50:	extreme size degression
GDE 0.50-0.64:	strong size degression
GDE 0.65-0.84:	moderate size degression
GDE 0.85-0.94:	weak size degression
GDE 0.95-1.00:	insignificant or no size degression

The GDE of the annual fixed costs of the large warehouse compared to the small warehouse corresponds to 0.62. This represents a strong size degression.

E.4.2.2 Dismantling plant

The **following procedure** was adopted for a rough estimate of the investment for the construction of dismantling plants:

- Analysis of the processes from the delivery of systems to their dismantling and the storage of the dismantled components. Modularization of dismantling and unloading processes in workstations. (In cooperation with the project areas **PB A** and **PB B**)
- Estimate of the required number of workstations and personnel based on the estimated process times depending on the number of systems to be processed.
- Estimate of the specific investments of the workstations in cooperation with IWF- TUBS and HTEE-TUBS as well as estimate of the required building floor space and the corresponding building and land investments.
- Estimate of the total investment and fixed costs for the defined capacity classes.

In the following explanations, it is assumed that dismantling is performed according to the principle of assembly (workshop layout) and that the material flow between the workstations is performed by industrial trucks (pallet trucks and forklift trucks), with a few exceptions. The batteries are stored and dismantled in separate buildings. The following sequence was identified in the process analysis (the number of employees required and the estimated employee and/or machine time per system are shown in brackets).

(1) After delivery in individual or collective shipments, each system is checked for external damage. The undamaged system is stored (1 MA, up to 10 minutes). Defective systems are subjected to special treatment in the F90 safety container and are not considered further here.

(2) After a short storage time, the system is transported from the warehouse to the neighboring dismantling building (1 worker, up to 10 minutes).

(3) The system is checked for possible hazards by a specialist using a diagnostic device. The specialist connects the system to a discharging device if it has a residual charge and the BMS permits this (1 MA, total: 10 minutes).

(4) The system is discharged to 0% SoC at the discharging device, provided the BMS permits this (no MA, 4 hours).

(5) After unloading, the system is dismantled at a dismantling workstation (2 employees, 1 hour). Meanwhile, the parts are roughly sorted and placed in different containers.

(6) The cell containers are transported to cell unloading devices (1 MA, max. 2 minutes).

(7) The cells are connected to cell discharging devices (1 MA, 5 seconds on average per cell, approx. 15 minutes per BEV equivalent ä 180 cells).

(8) The cells are discharged so that they have a voltage close to 0 volts (no MA, 4 hours).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

(9) The cells are disconnected from the cell discharging devices (1 MA, 2.5 seconds on average per cell, approx. 6 minutes per BEV equivalent ä 180 cells).

(10) The cells are stored in pallet cages until they are processed further.

The non-logistical processes described have been grouped into the following workstations:

System test station and **system unloading station** (3) and (4). The test station is equipped with various diagnostic devices and a collection of tools. It is installed on a trolley so that it can be moved directly to the system positioned on the unloading station. The discharging station allows the electrical residual charge to be fed back (optional) and is designed so that the system to be discharged can be positioned and checked while another system is still being discharged. In this way, the unloading station is used efficiently and empty runs of the industrial truck are avoided. The occupancy time of the test station is about 10 minutes, the occupancy time of the unloading station about 4 hours per system. The specific investments were estimated at EUR 5,000 per test station and EUR 14,000 per unloading station.

Dismantling station (5). The dismantling stations must be designed in such a way that the large and heavy components of the systems can be handled by two employees with as little physical strain as possible. The dismantled parts are sorted into appropriate containers in the immediate vicinity of the employees. The containers for the cells have enough volume to hold at least the cells from a large BEV system, ensure quick connection to the cell discharging devices and are designed to prevent short circuits in the cells. The specific investment for a dismantling station was estimated at around EUR 3,000.

Cell discharge station (6) to (9). The cell discharge stations allow the direct connection of cells (180 cells) and are capable of discharging them to voltages close to 0 volts within 4 hours using resistors. The specific investment for a cell discharging station was estimated at EUR 21,000.

The building floor area for the small dismantling plant was set at 200 square meters, that for the large one at 800 square meters. The required floor space of the separate warehouses was estimated at 150 square meters and 1,000 square meters respectively. This takes into account the temporary storage of the dismantled components (in mesh box pallets) with a space requirement of 70 square meters or 300 square meters.

Based on the framework conditions and specific investments described above, the **total investment for small dismantling facilities** was estimated at around EUR 560,000 and for **large dismantling facilities** at EUR 3,080,000 (see Annex 13). In both plant size classes, the system and cell unloading stations represent the bottlenecks (95 percent capacity utilization at 20 units/day), while the dismantling stations are utilized at around 36 percent in the small dismantling plant and 65 percent in the large dismantling plant. This means that the installation of additional system and unloading stations is sufficient to increase the mechanical capacity of the plants. Furthermore, it can be shown that the equipment of the small dismantling plant is robust against an increase in the average dismantling time to 115 minutes (+ 90 percent). In the large dismantling plant, however, the increase would lead to the need for 8 additional dismantling stations.

Fixed costs were estimated in the same way as for the transshipment warehouses. As a result, the annual **investment-related costs f**or small dismantling facilities are EUR 61,000/a, for large dismantling facilities EUR 336,000/a (see Annex 14). In the small dismantling plant, most of the costs are attributable to the specific building investment (36 percent), followed by the conveyor technology (11 percent), the cell unloading stations (11 percent) and the system testing and unloading stations (8 percent). In the large dismantling plant, the specific building investment also accounts for a large proportion of the investment-related costs (34 percent), while the cell discharging stations (20 percent) and the system testing and discharging stations (13 percent) also account for a large

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

proportion. The share of conveyor technology is only 5 percent.

In addition to the investment-dependent costs, the following **operating costs** were included in the annual costs independent of capacity utilization:

- Costs for management personnel: 15 percent surcharge on operating personnel costs.
- Ancillary operating costs (energy and cleaning costs, water, wastewater and refuse charges, property tax) of EUR 12/(sqm*a) in relation to the building area.
- Other overheads (mainly personnel administration): Surcharge of 15 percent on operating personnel costs.

Operating personnel costs were assumed to be variable due to the strategic approach and are therefore only included in the contribution margin calculation. However, they were still estimated in order to calculate the management personnel costs and other overheads, which are charged as surcharges on the operating personnel costs. To this end, the number of skilled workers required to achieve the maximum target turnover was calculated. A distinction was made between skilled workers for simple activities (logistics, dismantling, cell unloading) with an estimated gross employer salary of EUR 35,000 per year and skilled workers for more demanding activities (testing and system unloading) with an estimated gross employer salary of EUR 45,000 per year:

- Small dismantling plant: three-shift system; simple activities: 16 employees, demanding activities: 3 employees; operating personnel costs: EUR 695,000/a
- Large dismantling plant: three-shift system; simple activities: 80 employees; demanding activities: 6 employees; operating personnel costs: EUR 3.070,000/a

The **annual fixed cost**s add up to EUR 275,000 for the small dismantling plant and EUR 1,280,000 for the large dismantling plant (see Annex 15). The present size degression can be described as moderate (GDE: 0.67).

E.4.2.3 Mechanical processing plant

The method of differentiated surcharge rates based on Peters, Timmerhaus et al. was chosen for a rough estimate of the investment for mechanical processing plants.[23] The basis for the rough estimate is a list of the required machines and equipment as well as their specific investments. In addition to the purchase price for the system components supplied, the latter include the costs incurred for installation and for equipping the system with the appropriate measurement and control technology. The sum of the specific investments (hereinafter: base investment) is scaled to the investment in the overall plant using differentiated surcharges for other expenses directly or indirectly associated with the construction of a plant. It is assumed that the plant will be built on an existing site in the immediate vicinity of a hydrometallurgical processing plant and that no further storage facilities will be required.

The list of machines and equipment consists of the components specified by EC, which are required for process step 4B (mechanical destruction of cells), and the components specified by IPAT-TUBS, which are required for process step 5A (physio-mechanical electrode separation). The **basic investment** is therefore estimated at EUR 860,000 for a small mechanical processing plant and EUR 2,150,000 for a large plant. The **unknown direct capital investments** for pipelines, electrics, buildings, site development, operating equipment and ancillary facilities are estimated using the basic investment and the specific surcharge rates. For these investments, there is a surcharge of 65 percent on the basic investment. This means that the **total direct capital expenditure** (including the basic investment) for a small mechanical processing plant is approximately EUR 1,420,000, while

[23] Cf. Peters, Max S.; Timmerhaus, Klaus D.; West, Ronald E. (2004): Plant Design and Economics for Chemical Engineers. 5th Ed., International Ed. Boston [et al:] McGraw-Hill.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

the total for a large mechanical processing plant is approximately EUR 3,548,000. In addition, **indirect capital expenditure** is incurred for technical plant planning and construction supervision, construction management, approval procedures and fees for contractors. These are valued with a total premium of 57 percent on the basic investment. Unforeseen indirect investments are estimated at 21 percent. The total indirect investments therefore amount to EUR 675,000 and EUR 1,688,000 respectively. The addition of the direct and indirect investments yields the estimated **plant investment** for the construction of the small and large plants in the amount of EUR 2,100,000 and EUR 5,240,000 respectively (see Annex 16). Working capital, which is tied up in stockpiled raw materials and supplies, for example, is disregarded here.

The procedure for estimating the investment-related costs is the same as for the transshipment warehouses and dismantling plants. Indirect capital expenditure is amortized over 20 years. The annual investment-related costs therefore total EUR 255,000 for the small and EUR 640,000 for the large mechanical processing plant (see Annex 17). In addition to the investment-dependent costs, the following **operating costs** were included in the annual costs independent of capacity utilization:

- Costs for management personnel: 15 percent surcharge on operating personnel costs.
- Ancillary operating costs (energy and cleaning costs, water, wastewater and refuse charges, property tax) of EUR 12/(sqm*a) in relation to the building area.
- Other overheads (mainly personnel administration): Surcharge of 15 percent on operating personnel costs.

Assuming that simple logistical and control activities are to be performed during normal operation of the facilities, the staffing level is set at 6 persons (max. 2 per shift) in the small facility and 10 persons (3 per shift and 1 sprinter/sickness representative) in the large facility. With a gross employer salary of EUR 35,000 per employee and year, the annual operating personnel costs therefore amount to EUR 210,000 and EUR 350,000 respectively.

The **annual fixed costs** add up to EUR 320,000 (small mechanical processing plant) and EUR 760,000 (large mechanical processing plant, see annex).
18). The GDE of the annual costs of the large system compared to the small system is 0.38. This represents an extreme size degression in relation to the fixed costs.

E.4.2.4 Hydrometallurgical processing plant

The investment sum for a hydrometallurgical processing plant is known and is estimated by CM at around EUR 10 million excluding one-off costs for research and development. The annual costs are calculated below on this basis.

To determine the imputed costs, the technical useful life of the system is set at 20 years. With straight-line depreciation and an assumed residual value of 5 percent of the investment sum (EUR 500,000), the annual imputed depreciation amounts to EUR 475,000. The imputed interest for the average capital commitment of the system amounts to EUR 525,000, assuming an interest rate of 10 percent. The **annual imputed fixed costs** therefore add up to EUR 1 million.

Capacity utilization-independent pagatoric costs arise for repair and maintenance, investment-related insurance and administration. According to Peters, Timmermann et al. (2002), the **costs of repair and maintenance** in the form of wages and materials can be estimated as a percentage of fixed capital. The empirically determined percentage depends on the complexity of the process and the equipment as well as the prevailing operating conditions and ranges from 2 to 11 percent. In the case of the Chemetall plant, it is set at 10 percent, as this is a complex process with an innovative character and correspondingly complex equipment. In addition to the costs directly associated with maintenance, there are costs for operating materials (test chemicals, lubricants, etc.), which are calculated as a surcharge of 15 percent on the costs for repairs and maintenance. This results in

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

total repair and maintenance costs of EUR 1.150,000. The costs for **investment-related insurance and administration** (e.g. technology management) are each set at 1 percent and therefore amount to a total of EUR 200,000. Other fixed costs (e.g. fixed personnel costs) are not taken into account at this point, but are included in the process contribution margin calculation as direct material costs. The **annual pagatoric fixed costs** add up to EUR 1,350,000, the **total fixed costs** accordingly to EUR 2,350,000.

E.4.3 Estimate of process coverage contributions

E.4.3.1 Definitions and procedure

Process contribution margins are the contribution margins that can be achieved by processing the batteries in one process step. By definition, contribution margins are the surplus of variable revenues over variable costs. Unless otherwise stated, the revenues and costs caused by the flow of materials and energy, *labor costs and approximate transportation costs* are included in the *calculation* of *process* contribution margins in the following explanations. Due to a lack of technical testing, it was not possible to measure equipment and machine-related wear and tear and the associated imputed costs could not be directly allocated to the battery systems. They were included in the fixed costs as straight-line depreciation. The exclusion of imputed costs also allows the assumption made in the net present value analysis in **AS E.4.3**, on which the following explanations are based, that the contribution margins over a year are identical to the annual payments that cause them.

The estimate of process coverage contributions is used for the economic efficiency analysis and is partly based on the material and energy flow balances, which were compiled by the Öko-Institut in cooperation with the institutes of the Technical University of Brunswick. In this respect, it is consistent with the life cycle assessment performed. The material and energy flows for the mechanically destructive cell dismantling and the physio-mechanical electrode separation had to be additionally estimated.

The **functional units** of the LCA are differentiated according to the active materials “NMC” and “LFP” and each represent the material compositions of a mixture of different battery sizes (HEV, PHEV and BEV) standardized to one metric tonne. The material and energy flows of the process steps were standardized to the functional units accordingly. These units [t systems] are also used in the following explanations. To simplify matters, the mass fractions of the system components, the cells and the coating are assumed to be identical for both battery types, so that it is only necessary to differentiate between LFP and NMC active material from the hydrometallurgical active material preparation step onwards. Since LFP has a lower energy density than NMC, this means that the battery mixtures of NMC and LFP differ in terms of their average electrical storage capacity: A tonne of NMC battery mix has a higher capacity than a tonne of LFP battery mix.

The underlying **mass composition** of the functional unit is shown in Figure E-3. The left-hand pie chart shows components that are removed manually in the dismantling step. With the exception of the battery cells, which are processed further in the mechanical processing, they are recycled outside the system, recovered for energy (“for energy recovery”, “e. g. V.”) or thermally recycled (“for thermal utilization”, “partial V.”) and thus leave the LithoRec process. The pie chart on the right shows the components of the battery cells with their system-related mass fractions, which are separated in the mechanical processing step. While the cathode coating is further processed in the hydrometallurgical treatment process, the remaining components - aluminum chips from the cathode, graphite and copper from the anode, aluminum foil from the cell housing and residual materials such as electrolyte - are disposed of externally.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

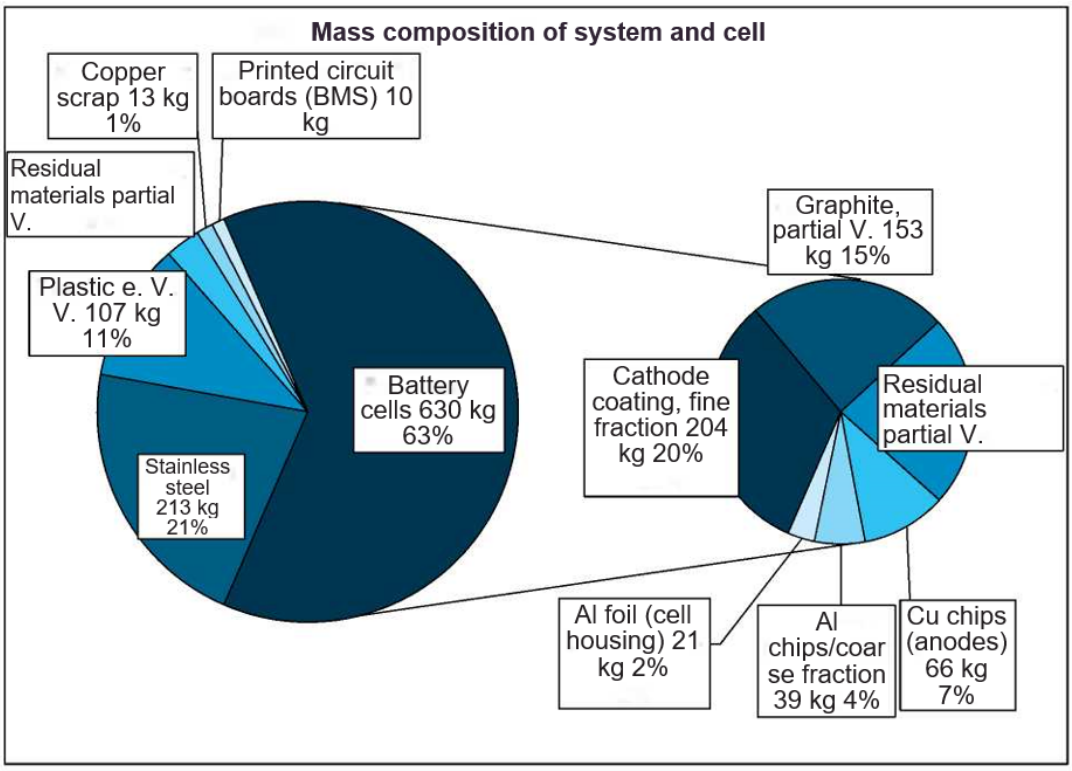


Figure E-3: Mass composition of the battery mixture used as a basis [t system]

Revenues and costs from material and energy flows

In cooperation with IPAT-TUBS, HCST, EC and CM, revenue and cost rates were determined for the substances and forms of energy included in the balance. They form the basis for the economic evaluation of the quantity structures. The incoming and outgoing material and energy quantities that exceed the system limits of the overall process are evaluated. Materials that are further processed within the system boundaries (e.g. cells that come from dismantling and go into mechanical processing) are not included. Revenue and cost rates are generally stated excluding VAT. There is a high degree of uncertainty, particularly with regard to revenue rates, for example for processed lithium and cobalt compounds and copper, which are also subject to high fluctuation. The same applies to energy cost rates. Against this background, sensitivity analyses to changes in certain revenue and cost rates are performed for each process after the process contribution margins have been determined.

Labor costs

Labor costs, which are a significant factor particularly in the internal transport and manual dismantling of batteries, are calculated on the basis of the processing times determined in the activity analysis or estimated on the basis of the personnel required to operate the systems. A distinction is made between two labor cost rates for specific requirements, each of which represents the employer's gross wage including ancillary costs. They amount to EUR 20/h (EUR 35,000/year) for simple tasks and EUR 25/h (EUR 45,000/year) for more demanding tasks. Employment-specific costs, for example for personnel management and administration, have already been taken into account in the estimate of fixed costs.

Transportation costs

Costs for transportation to and from points outside the system boundaries, such as the transportation of materials for disposal, were estimated for each process step for the total mass of the input and output materials to be moved. This was based on an average transport distance of 200 km and an

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

average transport cost rate of 5.60 per tonne and 100 kilometers. No further transportation costs were applied for the materials processed within the system, as these were already implicitly included in the calculation of wage costs. Any additional external transportation between spatially decoupled plants depends on the design and is only taken into account in **AP A.3**.

E.4.3.2 Contribution margin in dismantling

For one tonne of battery mix, **the material and energy flow-related contribution margin is EUR** 439. The largest positive contribution is made by the stainless steel housing, which represents a large proportion of current batteries in terms of mass and value (384 [EUR/t system], revenue rate 1.800 EUR/t). If the stainless steel housing is replaced by cheaper and lighter aluminum in the future, the contribution will fall to around EUR 240.[24] This may lead to a negative process contribution margin. Copper scrap (58 [EUR /t system], revenue rate 4.500 EUR/t) and printed circuit boards, e.g. from the battery management system (15 [EUR /t system], revenue rate 1.500 [EUR/t]) also make a significant contribution. The process also requires electrical energy to operate electric industrial trucks and tools. Any electrical energy recovered during discharging is initially used to cover the company's own requirements and then fed into the grid. However, the corresponding contribution margin is very low and is therefore neglected. The composition of the contribution margin is shown in Figure E-4.

The mass of materials procured or disposed of outside the system is approx. 370 [kg/t systems]. This corresponds to **transport-related costs** of 5 [EUR/t systems] rounded up.

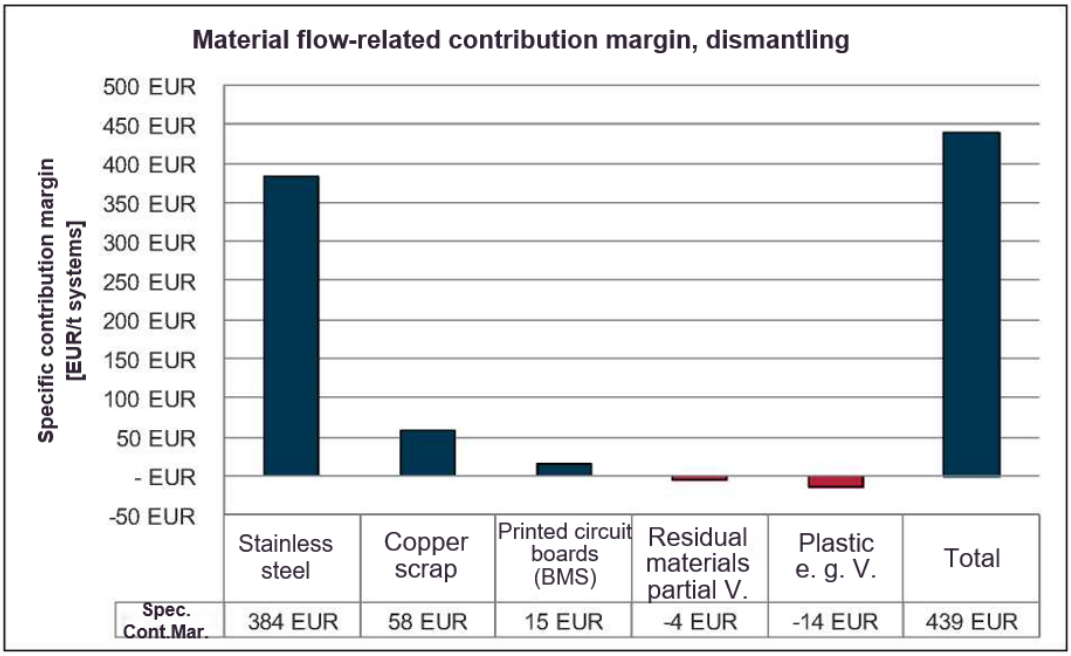


Figure E-4: Material flow-related contribution margin in dismantling

Table E-3: Functional units [t systems] and [BEV eq.] and conversion to PHEV and HEV systems

	t systems	BEV-eq.	PHEV	HEV
Normalization factor [BEV-eq.]	~ 3.0	1.0	0.5	0.1
System mass [kg]	1,000	330	165	33

[24] Calculated on BEV equivalents with 35 kg aluminum housing (instead of 70 kg stainless steel housing), value 50 EUR (instead of 126 EUR), again standardized to one ton of mixture.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

including				
Enclosure weight [kg]	213	70	35	7
Cell mass [kg]	630	200	100	20
including				
Cathode coating [kg]	183	58	29	6
Number of cells		180	90	18

The activities performed in the dismantling plant (transportation, testing, system unloading, dismantling and cell unloading) are associated with **labor costs**. Determining employee times on the basis of the functional unit [t systems] does not seem appropriate in this context. Instead, different battery variants are differentiated (HEV, PHEV and BEV or BEV equivalents) and the costs are initially determined on a per-unit basis. The conversion between the functional units is then performed on the basis of the assumptions shown in Table E-3. To simplify matters, it is assumed that a tonne of battery mix corresponds to approximately 3 BEV equivalents. The labor costs amount to 243 [EUR/t system] regardless of the size of the dismantling plant. The calculation for different battery types can be found in Table E-4. It is clear that the cost of processing a mixture of batteries depends very much on its composition. The estimated labor costs are to be understood as an average value for different battery types and refer approximately to a specific ratio of 60% BEV, 25% PHEV and 15% HEV batteries.

The **process contribution margin** in dismantling is identical for both capacity classes at 191 [EUR/t systems]. Due to the predominantly manual processes, there are no differences between the capacity classes. The composition of the process contribution margin is shown in Figure E-5.

Table E-4: Calculation of labor costs

Reference	Posts	Unit	Battery type		
			BEV	HEV	PHEV
Wages	Employee time for internal Transportation, cost rate 1	[hh:mm]	00:25	00:25	00:25
	Employee time Testing and system unloading, cost rate 2	[hh:mm]	00:10	00:10	00:10
	Employee time dismantling system (2 employees @ 1 h), cost rate 1	[hh:mm]	02:00	01:00	00:12
	Employee time Cell discharge Cost rate 1	[hh:mm]	00:24	00:12	00:02
	Labor costs Cost rate 1 (20 EUR/h)	EUR/unit	56.33	32.33	13.13
	Labor costs Cost rate 2 (25 EUR/h)	EUR/unit	4.17	4.17	4.17
Labor costs	Labor costs (LC) (rounded)	EUR/unit	60.00	36.00	17.00
	per tonne of systems	EUR/t	181.00	219.00	524.00
Wage costs, standardized	LK for BEV eq. standardization	EUR/unit	60.00	30.00	6.00
	LK with FfU* 33% (applied)	**EUR/unit**	**80.00**	**40.00**	**8.00**
	per tonne of systems (rounded up)	**EUR/t**	**243.00**	**243.00**	**243.00**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

*) ***FfU: Factor of uncertainty.***

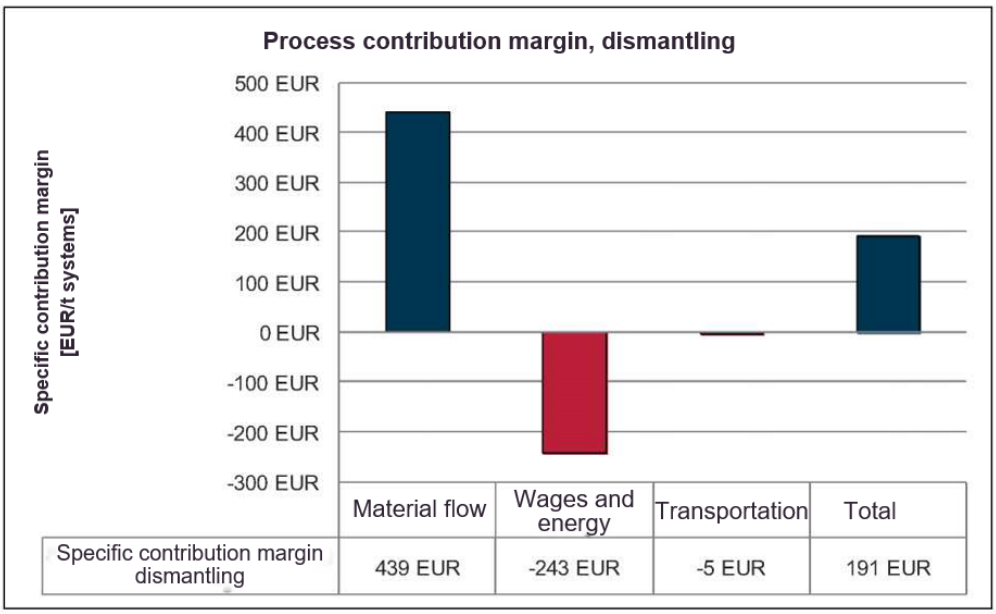


Figure E-5: Process contribution margin in dismantling

E.4.3.3 Contribution margin in mechanical processing

The **material and energy flow-related contribution margin** is 340 [EUR/t systems]. The largest contribution is made by the copper chips in the anode. Assuming the high-purity separation of the chips and their briquetting capability, it amounts to 414 [EUR/t systems] at a revenue rate of 6.300 [EUR/t]. The main input materials are sodium hydroxide (NaOH), which is required for hydrofluoric acid washing (9 [EUR/t systems] at a cost rate of 250 [EUR/t])[25]. The required quantities of NaOH and the substances sodium fluoride (NaF, 22.65 [kg/t system]) and sodium carbonate (Na_2CO_3, 17.95 [kg/t system]) produced by the chemical reaction were estimated stoichiometrically by the Öko-Institut. The hazardous waste disposal (SME) of the NaF-Na_2CO_3 mixture leads to costs of 16 [EUR/t systems]; alternatively, the substances could possibly be separated and sold in high-purity form. Further significant costs may arise from the use of nitrogen to create an inert atmosphere or to deactivate the chemical activity; however, these have not been included due to the lack of research into the need for use and the possibility of recycling. The specific electricity requirement in mechanical processing was generously estimated at 261 kWh/[t systems] based on the connected loads of the equipment and machines and the cell throughput. The composition of the material and energy flow-related contribution margin is shown in Figure E-6.

The mass of materials procured or disposed of outside the system is approx. 500 [kg/t systems]. This leads to **transport-related costs** of rounded up 6 [EUR/t systems]. The **labor costs** in the small mechanical processing plant are 150 [EUR/t systems], in the large plant 20 [EUR/t systems] (see Table E-5). The estimate of labor costs is based on the explanations in E.4.2.3 and relates the hourly labor costs to the nominal throughput of the system. If the throughput is lower, the labor costs must be weighted correspondingly higher.

The **process contribution margin** in mechanical processing is estimated at 184 [EUR/t systems] in the small plant and 314 [EUR/t systems] in the large plant (see Figure E-7). In terms of cell mass,

[25] Hydrofluoric acid washing is necessary because fluorine-containing compounds may be released from the binder of the cathode coating (polyvenylidene fluoride, PVdF) and from the conducting salt in the electrolyte (lithium hexafluorophosphate, LiPF6) during the thermal processes.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

this corresponds to 292 [EUR/t cells] and 498 [EUR/t cells] respectively.

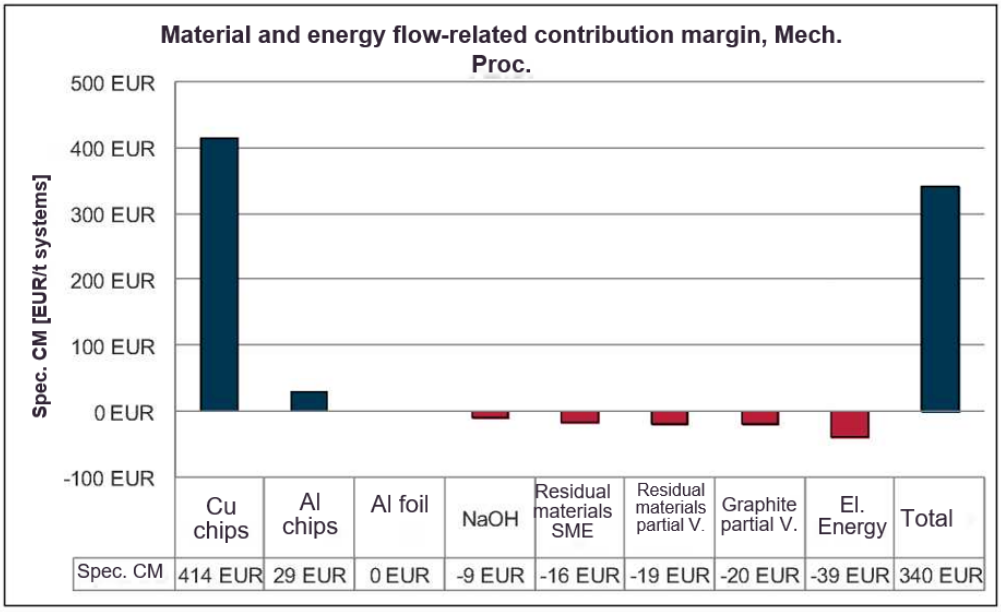


Figure E-6: Material and energy flow-related contribution margin in mechanical processing

Table E-5: Labor costs in mechanical processing

Reference	Unit	Small work	Large work
Nominal cell throughput	kg cells/h	170	1,700
Wage costs for operating personnel	EUR/h	40.00	50.00
Special labor costs	EUR/t cells	235.29	29.41
Special labor costs	EUR/t systems	148.23	18.53
Specific labor costs (recognized)	**EUR/t systems**	**150.00**	**20.00**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

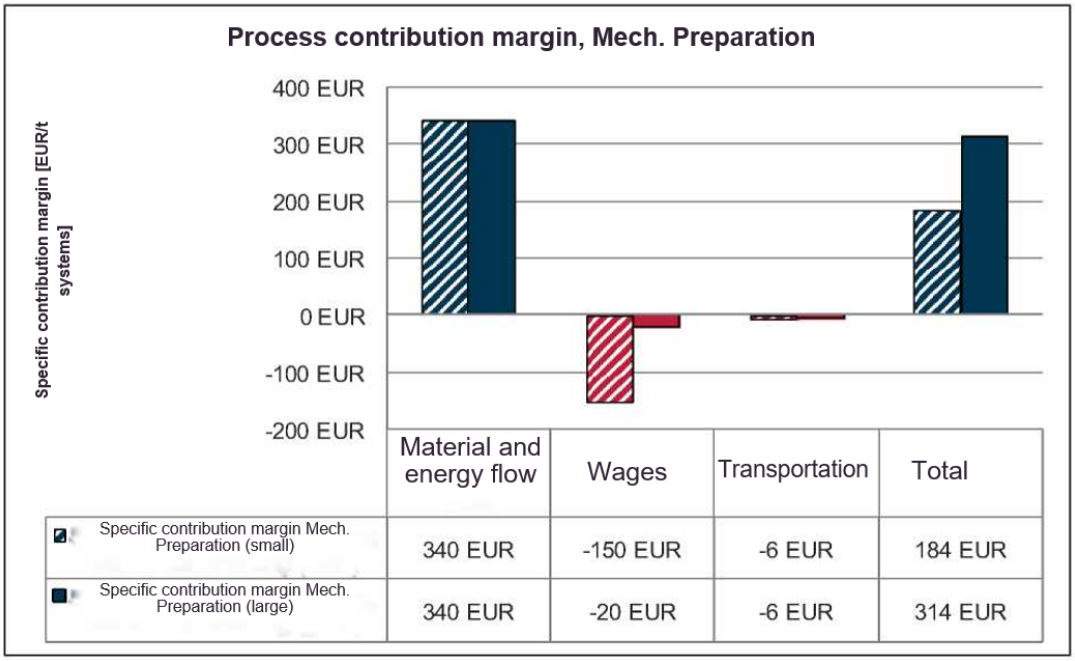


Figure E-7: Process contribution margin in mechanical processing

E.4.3.4 Contribution margin in hydrometallurgical processing

The main product of mechanical processing, the fine fraction of the cathode coating (active material), is used in hydrometallurgical processing. The powdery solid is separated into a lithium salt solution and another solution in various precipitation processes using hydrogen peroxide, sulphuric acid and electrical energy. The amount of incoming energy and substances as well as the type and value of the solutions obtained depend on the type and condition of the processed active material. The lithium salt solution is then processed using electrical energy and steam in various chemical processes to obtain lithium hydroxide monohydrate or lithium carbonate. The following presentations, differentiated according to the active material types lithium nickel manganese cobalt (NMC) and lithium iron phosphate (LFP), are based on preliminary results of various tests by CM, HCS and IPAT-TUBS. As some of the data is confidential, either only the market prices of the substances used in the reference scenario or only their quantities are stated in addition to the aggregated contribution margins.

Processing one tonne of **NMC systems** yields 73 kg of lithium hydroxide monohydrate and 184 kg of transition metal salt solution. The latter contains cobalt, nickel and manganese sulphates in varying proportions and is suitable for the production of new active material. The proportions of transition metal salts are directly dependent on the composition of the active materials. The proportions on which the calculation is based were determined by HCS for a batch originating from the CM process and can be found in Table E-6. The value of this solution is heavily dependent on the volatile prices of the listed transition metals cobalt and nickel and is estimated at EUR 1.300/t to EUR 2.100/t. Potential impurities could require further processing, which would greatly reduce the value. A revenue rate of EUR 1.300/t is applied in the reference scenario. The approximate market price of EUR 8,000/t is used for lithium hydroxide monohydrate. In the processing of NMC systems, 203 [EUR/t systems] is spent on input materials and energy. This is offset by 826 [EUR/t systems] from the sale of the recovered recyclables. The **material flow-related contribution margin** in the reference scenario is therefore 623 [EUR/t systems] in relation to NMC systems.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Table E-6: Composition of the transition metal salt solution

Transition metal salt	Concentration in solution [g/l]
Cobalt(II) sulfate heptahydrate $CO_2SO_4 \cdot H_2O$	55.1
Nickel(II) sulfate heptahydrate $Ni_2SO_4 \cdot H_2O$	53.1
Manganese(II) sulphate monohydrate $Mn_2SO_4 \cdot H_2O$	48.2

Processing one tonne of **LFP systems** produces 46 kg of lithium hydroxide monohydrate and 184 kg of residual materials. In contrast to NMC, the LFP active material does not contain any valuable transition metals. There are currently no known economically viable recycling options for the remaining iron phosphate compounds. These residual materials must be disposed of as hazardous waste (cost rate: 400 [EUR/t]) at a cost of 73 [EUR/t systems]. The required input materials and energy lead to costs of 85 [EUR/t systems]. The total costs of 158 [EUR/t systems] are offset by revenues from the sale of lithium hydroxide monohydrate amounting to 367 [EUR/t systems]; the **material flow-related contribution margin** for LFP systems corresponds to 209 [EUR/t systems] in the reference scenario.

The total mass of the materials to be transported is 643 [kg/t systems] in the case of NMC and 523 [kg/t systems] in the case of LFP. Accordingly, 8 and 6 [EUR/t systems] respectively are used for the **transport-related costs.** CM estimates **labor costs and other general operating costs by applying** a flat-rate mark-up of 30 percent to the costs of input materials and energy. This leads to costs of around 60 [EUR/t systems] in relation to the material flow and energy costs for NMC systems, which are also applied to LFP systems for the sake of simplicity.

The process contribution margin in the reference scenario for NMC systems is 555 [EUR/t systems]. For LFP systems, it amounts to 143 [EUR/t systems] (see Figure E-8).

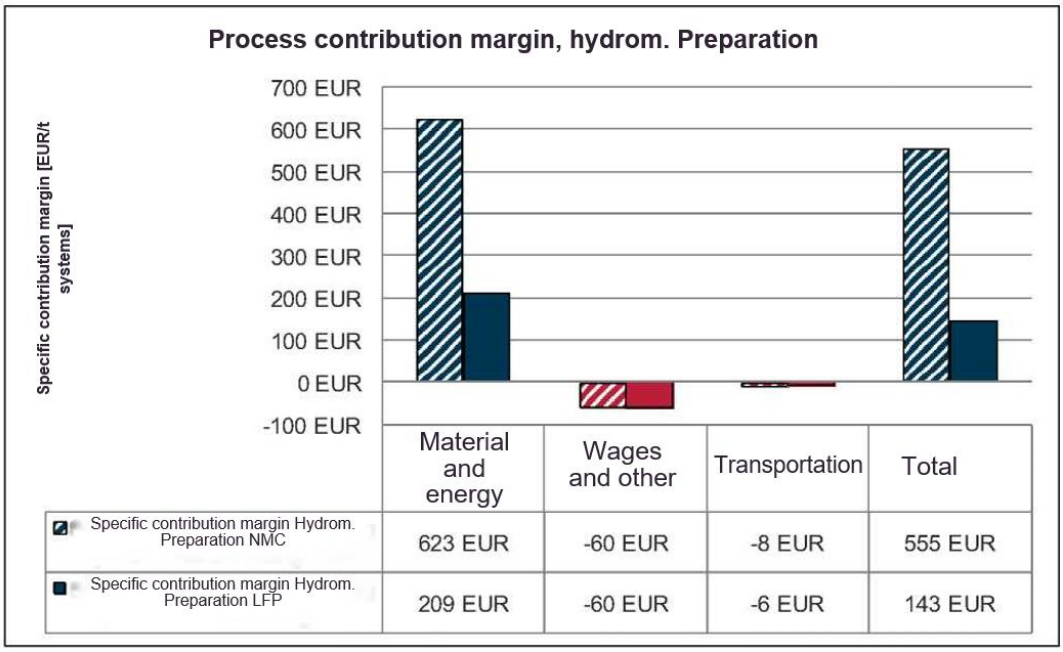


Figure E-8: Contribution margin in hydrometallurgical processing for NMC and LFP systems

E.4.3.5 Total process contribution margin and sensitivity analysis

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The total process contribution margin is the sum of the process contribution margins in the dismantling plant, the mechanical processing plant and the hydrometallurgical processing plant. As the process coverage contributions in the mechanical processing plant vary depending on the capacity class and in the hydrometallurgical processing plant depending on the battery type, the GDB can be differentiated according to the size class of the processing plant (small and large) and according to the battery types processed (NMC and LFP) (see Table E-7).

Table E-7: Case distinctions and total process coverage contributions

Mechanical capacity Processing plant	Small 1,000 to 2,000 [t/a]		Large 10,000 to 20,000 [t/a]	
Active material	NMC	LFP	NMC	LFP
Case name	K-NMC	K-LFP	G-NMC	G-LFP
GDB (reference) [EUR/t systems]	930,-	518.00	1,060,-	648.00

Based on the described fluctuation and high uncertainty regarding the prices of energy sources and materials, four price development scenarios are considered in addition to the reference case described above:

Recyclable material revenue -20% and recyclable material revenue +20% scenarios: These scenarios reflect the high level of uncertainty regarding marketable recyclable materials. Revenues from the sale of recyclable materials are 20 percent lower or higher than in the reference scenario. This can be due to falling or rising market prices as well as lower or higher recycling efficiency.

Energy costs +50% scenario: This scenario depicts future price increases and/or higher quantities of energy sources used. The energy source-related costs increase by 50 percent.

Scenario input material costs +20%: The procurement costs for the input materials used - sulphuric acid, hydrogen peroxide and sodium hydroxide - increase by 20 percent.

Disposal costs scenario +20%: The costs for the disposal of substances, e.g. for energy and thermal disposal, are 20 percent higher.

In all of these cases, **deviating revenues** from recyclable materials have the greatest influence on the overall process contribution margin. The greatest negative impact can be seen in the processing of LFP batteries. With K-LFP, the GDB drops by a good -50 percent. This is primarily due to an approximate halving of the process coverage contributions in all three processes. At G-LFP, the effect is somewhat dampened by lower variable (wage) costs in the mechanical processing plant; the deviation is -40 percent. Although the absolute effect of the reduction in the price of recyclable materials is significantly higher in the processing of NMC (-346 compared to -254 [EUR/t systems]), it is somewhat lower in relative terms at -37% (K-NMC) and -33% (G-NMC). The reverse positive effect is achieved by increasing the revenue from recyclable materials by +20%.

Rising energy costs also lead to a sharp reduction in the GDB, but the effect is at a much lower level. The deviation is greater for NMC due to the higher energy requirement in hydrometallurgical processing and amounts to between -9.2 percent (K-NMC) and -5.6 percent (G-LFP). The absolute deviation is -86 [EUR/t systems] (NMC) and -36 [EUR/t systems] (LFP).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Rising input material costs only have a minor impact on the economic efficiency of the process.[26] The relative deviations with a variation of +20 percent are between -2.3 percent (K-LFP) and -1.4 percent (G-NMC). Due to the slightly higher resource requirements, the absolute deviation in the processing of NMC compared to LFP is somewhat higher (-15 and -12 [EUR/t systems] respectively).

At -29 [EUR/t systems], rising disposal costs have a significantly higher impact on the processing of LFP than on the processing of NMC (-14 [EUR/t systems]), as the **hydrometallurgical** processing of LFP cathode material generates a large amount of residual materials. The deviation from the GDB is between -5.6% (K-LFP) and -1.3% (G-NMC).

The **differences** in the scenarios are illustrated in Figure E-9 (K-NMC), Figure E-10 (G-NMC), Figure E-11 (K-LFP) and Figure E-12 (G-LFP) (relative deviation in each case) and Figure E-13 (abs. deviation).

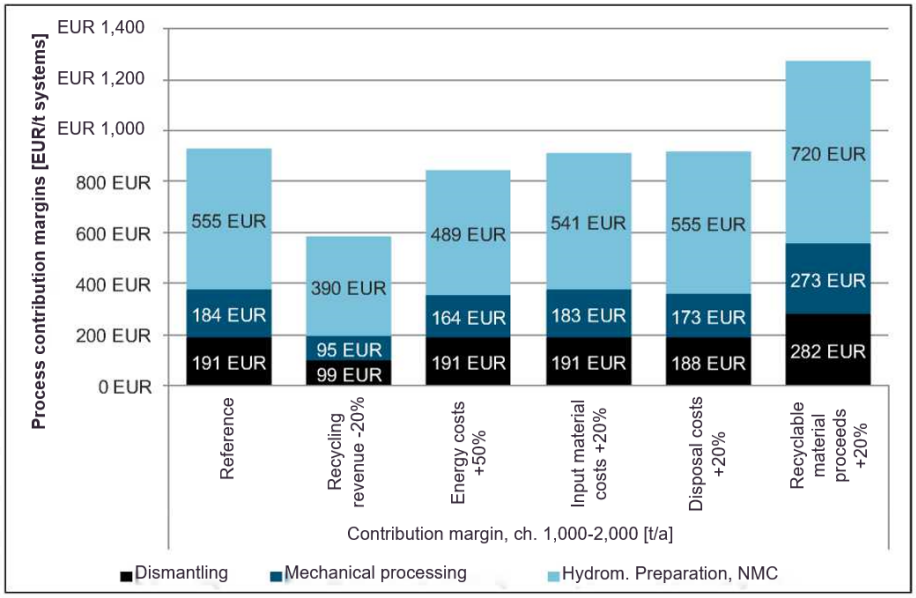
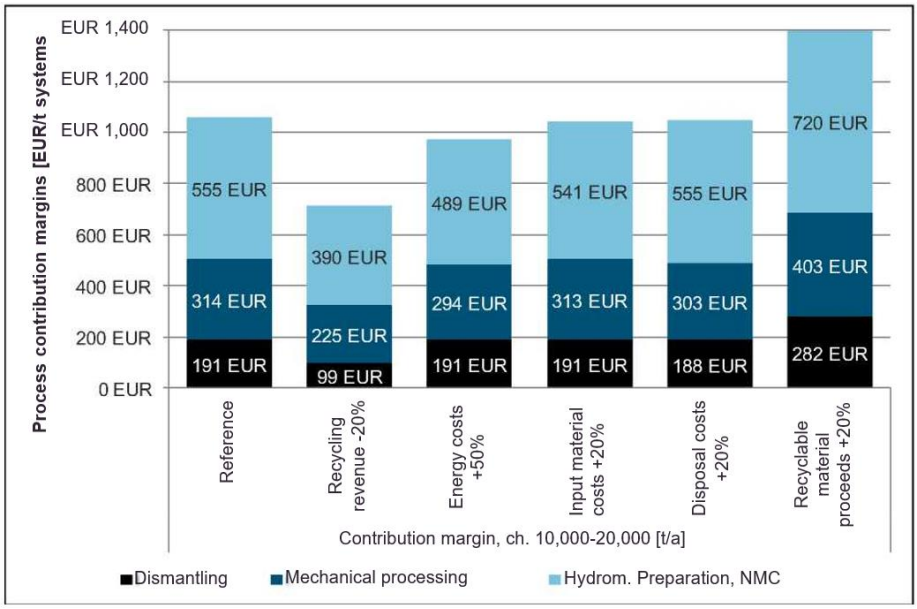


Figure E-9: Sensitivity analysis regarding process coverage contributions (K-NMC)



[26] However, the possible need for additional input materials, e.g. nitrogen, can significantly change this situation.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure E-10: Sensitivity analysis regarding process coverage contributions (G-NMC)

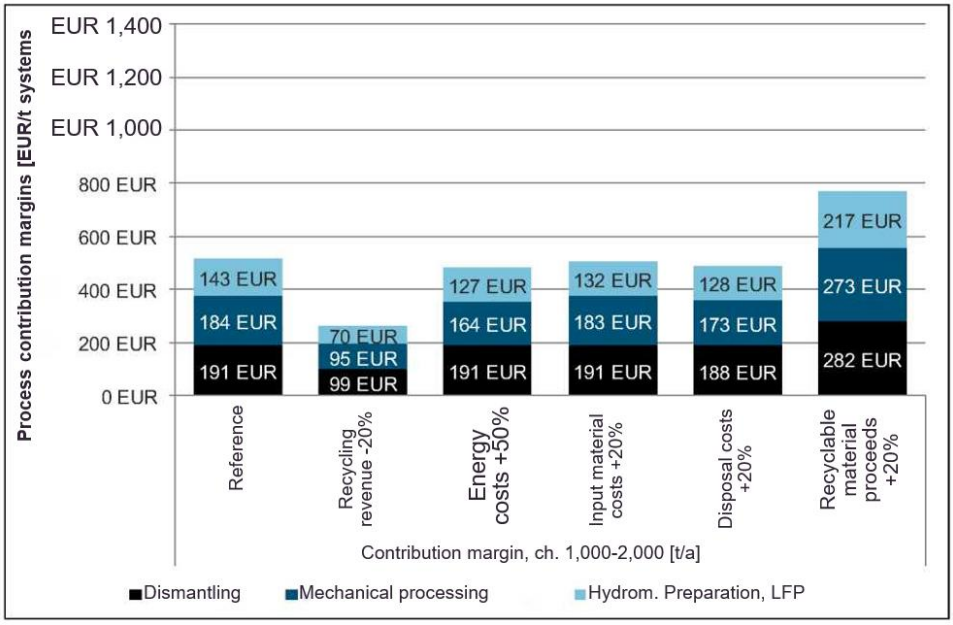


Figure E-11: Sensitivity analysis regarding process coverage contributions (K-LFP)

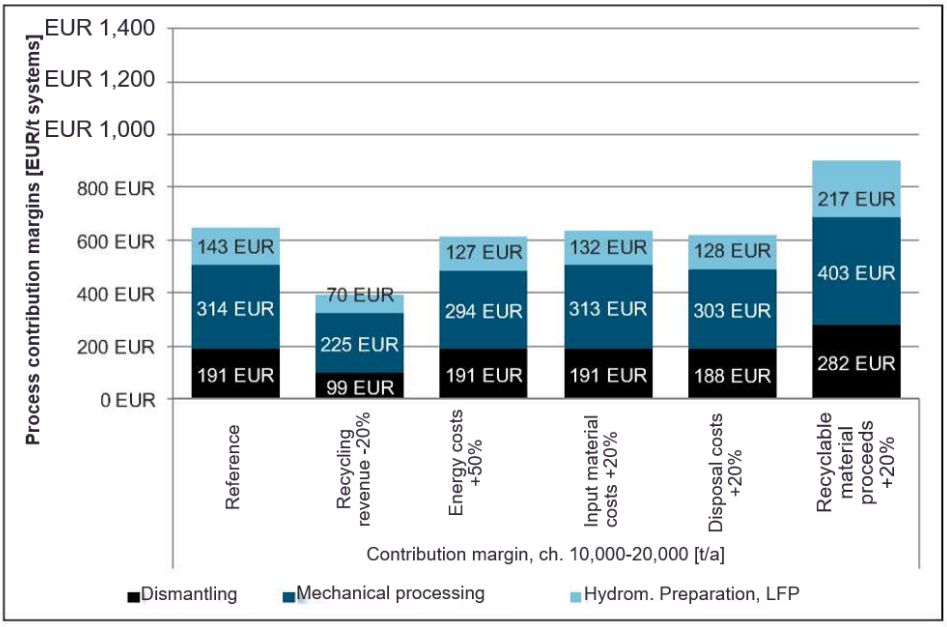


Figure E-12: Sensitivity analysis regarding process coverage contributions (G-LFP)

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

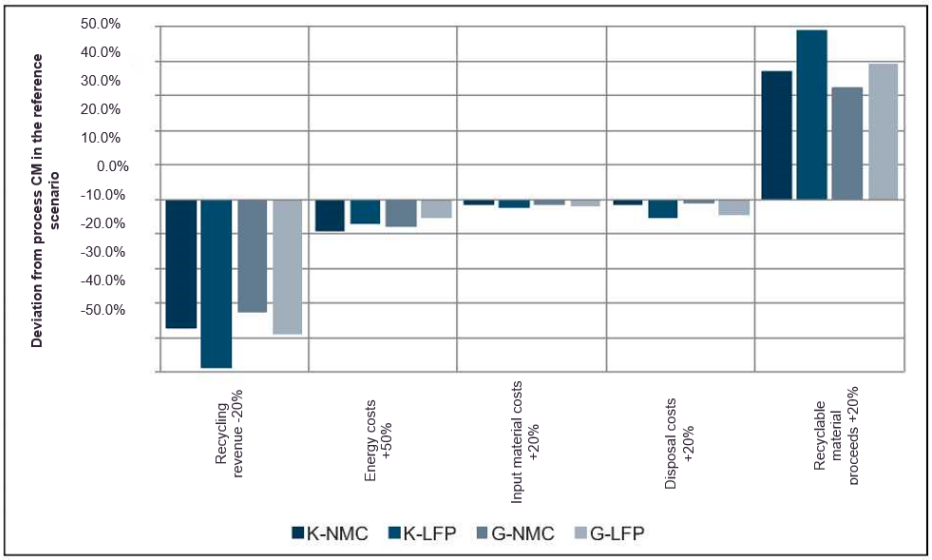


Figure E-13: Relative deviations of the scenarios from the reference GDB

E.4.4 Break-even points

Based on the calculated annual fixed costs and the process contribution margins, the potential profitability of the individual processes under consideration and of the overall process can be evaluated. This takes the form of a break-even analysis. In the break-even analysis, the critical quantity of batteries to be processed annually at which the fixed costs of a process or the overall process are just covered is determined in the specific case. A throughput below the break-even point leads to a loss (negative result), a throughput above the break-even point leads to a profit (positive result). The throughput and the break-even point refer to the functional unit [t systems]. The calculated break-even points, in combination with forecasts for the volume of used batteries, allow statements to be made about the point at which a plant can be operated economically. However, this is limited by some uncertainties and inaccuracies:

■ The estimated **fixed costs** of the processes relate to plants for which either no construction plans are yet available or which are not yet in operation as intended. The methods used in the early rough estimate are based on a number of assumptions and premises, and the accuracy of the results is naturally in the range of up to ± 30 percent.

■ The **functional unit** of the battery mixture [t systems] is a simplification; the material composition of the mixture is very specific and can vary greatly in individual cases, especially when considering a specific battery system.

■ The estimated contributions**process coverage** are largely based on laboratory or stoichiometrically determined material and energy flows for a few selected battery types. The underlying revenue and cost rates represent a snapshot of the market, can vary widely in practice and are subject to high dynamics. As already shown in the sensitivity analysis, the actual process coverage contributions can deviate significantly, by up to ± 50 percent within the scenarios examined.

■ The **statics and linearity of revenue and cost structures** in relation to throughput is a simplifying premise of the break-even analysis. In practice, for example, fixed costs, economies of scale and learning curve effects can be expected as throughput increases. In this specific case, the highest reliability of the calculated break-even points can be seen with a throughput in the range of the stated capacity intervals of the plants. For this reason, the small dismantling and mechanical processing plants cannot be directly compared with the hydrometallurgical processing plants.

■ The **volume of used batteries is highly uncertain** (cf. **AP A.1**), so that any time determinations only apply under the assumption of a certain scenario.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

In order to counter these uncertainties, the break-even analysis is performed in two stages and based on scenarios: **In the first step**, scenarios relating to the processes and composition of the used battery volume are created to determine throughput-related break-even points. The results are presented using coherent, meaningful and easy-to-understand break-even charts. **In the second step**, the throughput-related profit thresholds are set in relation to the used battery volume scenarios developed in **AP A.1** in order to determine time-related profit thresholds.

E.4.4.1 Throughput-related profit thresholds

Scenarios relating to the processes

On the one hand, the scenarios relating to the processes are derived from the uncertainties associated with the investment estimates. They represent an (average) accuracy interval of 20 percent around the estimated fixed costs of the individual processes. On the other hand, they result from the uncertain process coverage contributions. The sensitivity analysis showed that revenue from recyclable materials is the most significant factor influencing process contribution margins. Accordingly, the scenarios represent the interval of process coverage contributions in the event of a variation in material revenue of plus or minus 20 percent.

In the **reference scenario**, both fixed costs and process contribution margins correspond to the reference values presented above. In the **negative extreme scenario** ("worst-case scenario"), the fixed costs are 20 percent higher than in the reference case; the process contribution margins correspond to the case of 20 percent lower revenue from recyclable materials. In the **positive extreme scenario** ("best-case scenario"), the fixed costs are 20 percent lower than in the reference case, while the process contribution margins relate to the case of 20 percent higher revenue from recyclable materials.

Scenarios regarding the composition of the used battery volume

The scenarios regarding the composition of the used battery volume are based on the uncertain market and technology development with regard to the battery types that are becoming established. As the individual battery types lead to different contribution margins in hydrometallurgical processing, the composition of the used battery volume is a key factor influencing the profitability of recycling. Only NMC and LFP battery types are considered, but in different proportions. In addition to the two extreme cases **(exclusively NMC and exclusively LFP** systems), the "**NMC80:LFP20**" scenario is also considered, in which the used battery volume specifically consists of 80 percent NMC systems and 20 percent LFP systems.

Economic efficiency of individual processes

A comparison of the profitability of individual processes shows a clear difference in terms of the respective break-even point. In the reference case, this is only achieved in the **large dismantling plant** at more than 6.700 [t systems/a], while the **large mechanical processing plant** already becomes profitable at approx. 2.400 [t systems/a]. The profitability of the **hydrometallurgical processing plant** depends largely on the composition of the used battery mass processed. With the exclusive processing o**f NMC systems**, the break-even point is reached at 4.200 [t systems/a]. A **mixed volume** (NMC80:LFP20) leads to a break-even point of 5,000 [t systems/a]. However, if only **LFP systems** are processed, it is at the upper capacity limit of the plant at 16.400 [t systems/a].

The break-even points for all individual processes and the overall process depending on the scenarios are shown in Table E-8. It becomes clear that some plants or processes cannot be operated economically under unfavorable conditions (high fixed costs, low contribution margins) if the respective theoretical break-even point exceeds the capacity of a plant. This is the case in the small dismantling plant (3.300 [t systems/a]), in the small mechanical processing plant (4,000 [t

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

systems/a]) and in the hydrometallurgical processing plant with predominantly or exclusively processing of LFP systems (40.300 [t systems/a]). Figure E-14 illustrates the strong influence of the composition of the used batteries on the economic efficiency of the hydrometallurgical process.

Table E-8: Throughput-related break-even points for all individual processes and the overall process

Process	Break-even point [t systems/a]		
	Reference scenario	Negative extreme scenario	Positive Extreme scenario
Dismantling unit, large	6,700	15,500	3,600
Mechanical processing plant, large	2,400	4,100	1,500
Hydrom. Processing plant, NMC	4,200	7,200	2,600
Hydrom. Processing plant, LFP	16,400	40,300	8,700
Hydrom. Preparation plant, NMC80:LFP20	5,000	8,700	3,000
Overall process (large), NMC	4,100	7,400	2,500
Overall process (large), LFP	6,800	13,400	3,900
Overall process (large), NMC80:LFP20	4,500	8,100	2,700
Dismantling unit, small	1,400	3,300	800
Mechanical processing plant, small	1,700	4,000	900

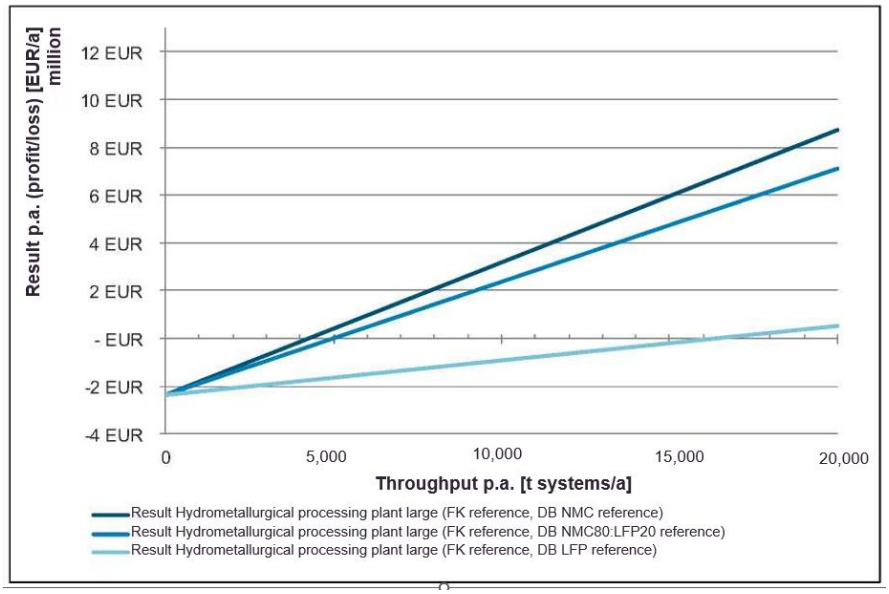


Figure E-14: Profit threshold diagram for hydrometallurgical reprocessing with different compositions of used batteries

Overall process efficiency for NMC systems: reference scenario compared to the positive and negative extreme scenarios

Figure E-15 shows the absolute results (overall result) and the average results (result per tonne of battery systems) as a function of the annual throughput when processing NMC systems only.

In the **reference scenario**, the break-even point is reached at approx. 4.100 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is EUR 11.5 million (EUR 767 [t systems/a]).

In the **negative extreme scenario** (high fixed costs, low contribution margins), the break-even point is only reached at 7.400 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is EUR 5.4 million (EUR 363 [t systems/a]).

In the **positive extreme case** (low fixed costs, high contribution margins), the break-even point is

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

already reached at 2.500 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is EUR 17.6 million (EUR 1.171 [t systems/a]).

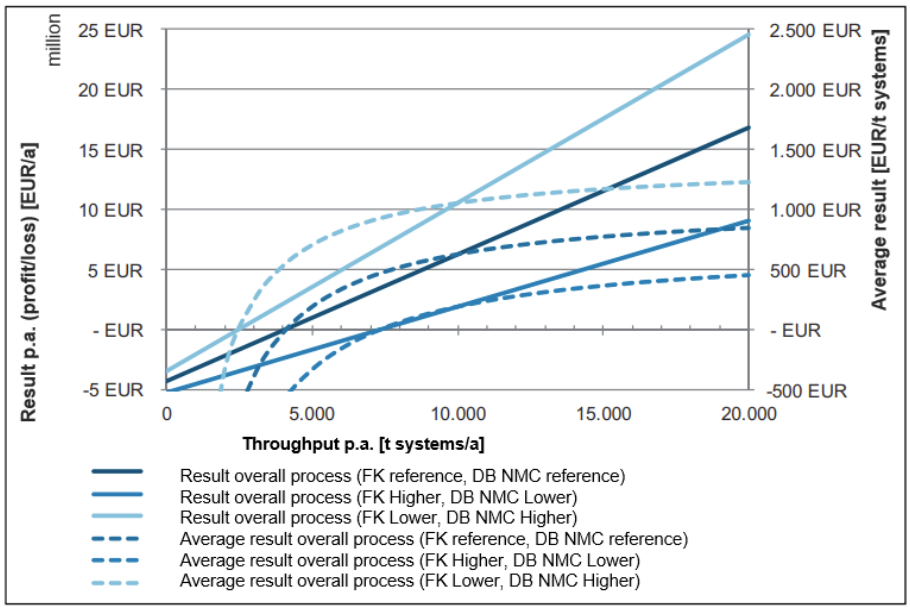


Figure E-15: Break-even diagram of the overall process for NMC systems

Overall process efficiency for LFP systems: reference scenario compared to the positive and negative extreme scenarios

Figure E-16 shows the results as a function of the annual throughput when processing LFP systems only.

In the **reference scenario**, the break-even point is reached at approx. 6,800 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is EUR 5.3 million (EUR 355 [t systems/a]).

In the **negative extreme scenario** (high fixed costs, low contribution margins), the break-even point is only reached at 13.800 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is only EUR 0.6 million (EUR 43 [t systems/a]).

In the **positive extreme scenario** (low fixed costs, high contribution margins), the break-even point is reached at 3,900 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is EUR 10.0 million (EUR 668 [t systems/a]).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

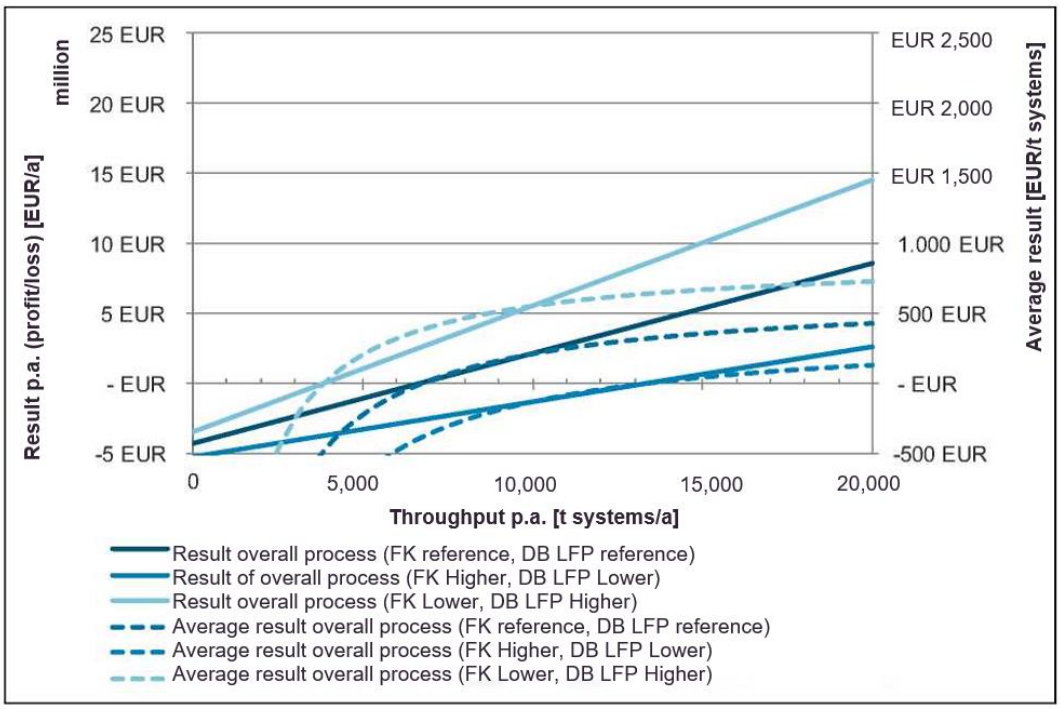


Figure E-16: Break-even diagram of the overall process for LFP systems

Overall process efficiency for mixed volumes: Reference scenario in comparison of the positive and negative extreme scenarios

Figure E-17 shows the results as a function of the annual throughput when processing a volume consisting of 80 percent (specific) NMC systems and 20 percent LFP systems (NMC80:LFP20).

In the **reference scenario**, the break-even point is reached at approx. 4,500 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is EUR 10.3 million (EUR 685 [t systems/a]).

In the **negative extreme scenario** (high fixed costs, low contribution margins), the break-even point is reached at 8.100 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is EUR 4.5 million (EUR 300 [t systems/a]).

In the **positive extreme scenario** (low fixed costs, high contribution margins), the break-even point is reached at 2.700 [t systems/a]. The theoretical profit for 15,000 [t systems/a] is EUR 16.1 million (EUR 1.070 [t systems/a]).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

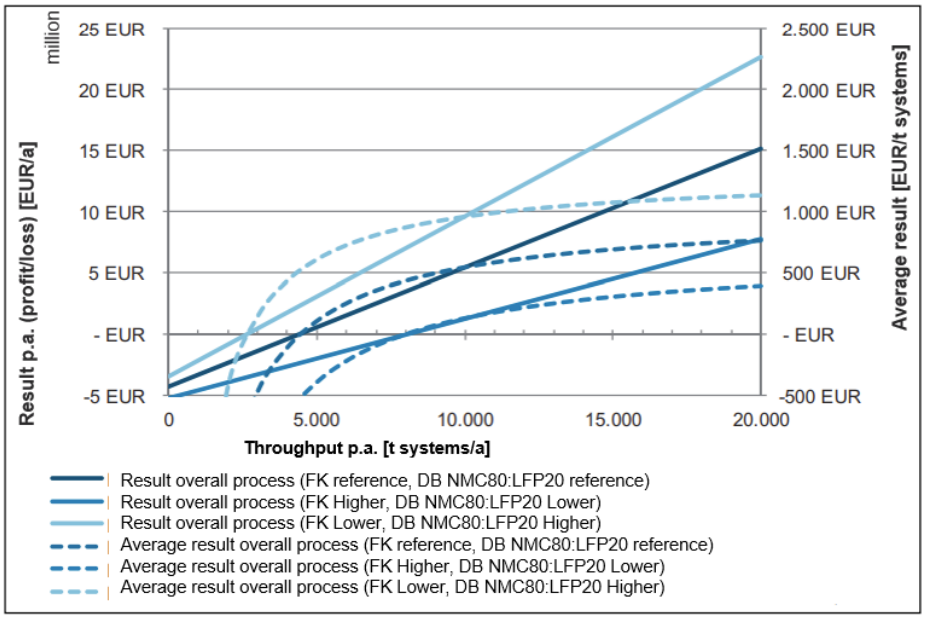


Figure E-17: Break-even diagram of the overall process for mixed volumes

Overall process efficiency depending on the composition

Figure E-18 shows the annual result as a function of throughput and composition of the used battery volume for the reference scenario with regard to fixed costs and contribution margins. The specific proportion of LFP systems is shown on the ordinate axis and the annual throughput in [t systems/a] is shown on the abscissa. The annual result (profit/loss) of the overall process is divided into five differently shaded intervals.

The diagram shows the throughput and composition-related break-even point (transition from the light gray shaded area to the blue-gray shaded area). For example, a composition of 80 percent LFP systems (20 percent NMC) results in a break-even point of 6,000 [t systems/a]. Conversely, it can be seen how high the proportion of LFP systems can be in order to achieve a positive result with a given throughput. In order to be able to operate recycling profitably with an assumed annual throughput of 5,000 systems, for example, the proportion of LFP systems must not exceed ~42 percent.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

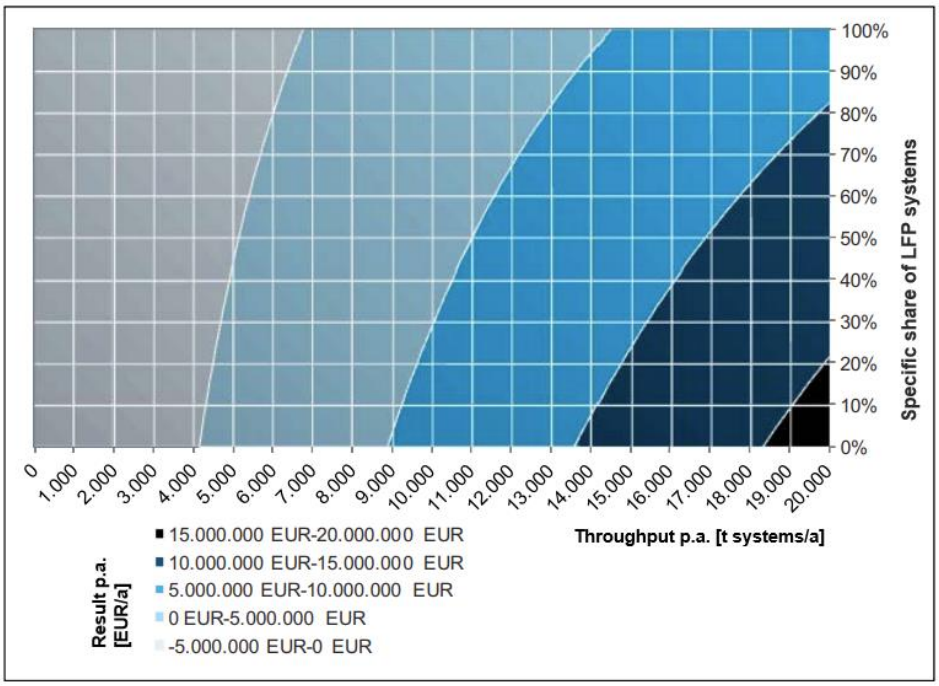
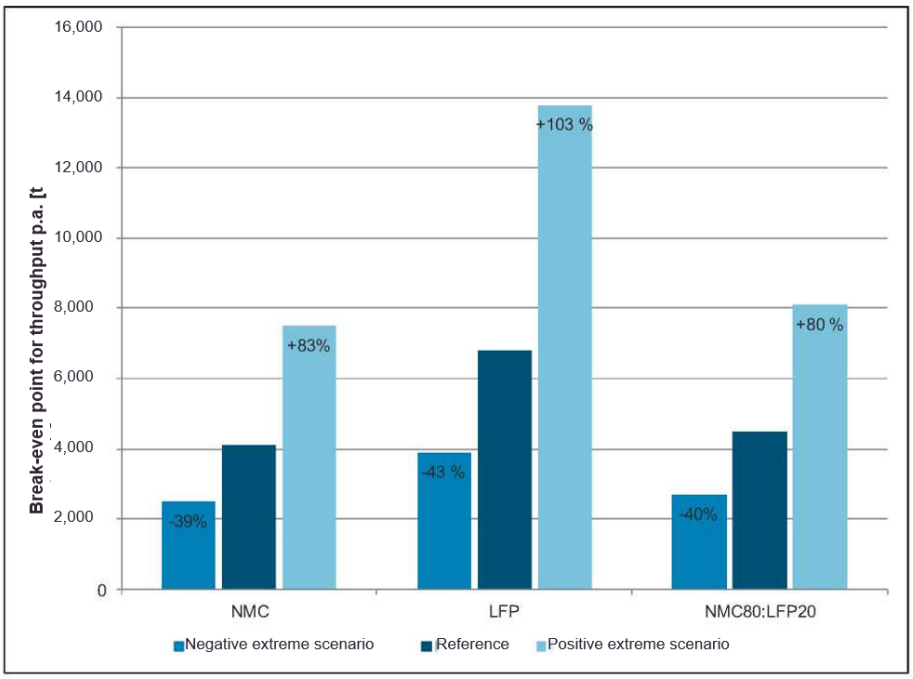


Figure E-18: Annual result as a function of throughput and composition of the used battery volume

Comparison of the scenarios

The comparison of the scenarios shows considerable differences with regard to the break-even points. In the negative extreme scenario, for example, between 3 times (NMC only) and 3.5 times (LFP only) as many batteries are required to cover costs as in the positive reference scenario (see Figure E-19). The higher the specific proportion of LFP systems, the stronger this effect is.

Analogous to the individual process analysis, it is clear that the break-even points of the overall process depend heavily on the composition of the used battery volume. The break-even point rises disproportionately with the increase in the proportion of LFP systems. If only LFP systems are processed, the break-even point in the reference case is 6.800 [t systems/a], in the case of NMC systems it is 4.100 [t systems/a]. A good two-thirds more LFP systems are therefore required to reach the break-even point than in the case of NMC systems.



This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Figure E-19: Break-even points depending on the scenarios and percentage deviation of the extreme scenarios from the reference scenario

E.4.4.2 Time-related profit thresholds

Figure E-20 and Figure E-21 use block diagrams to show the break-even points for the individual processes and the overall processes depending on the scenarios for used battery volumes. They graphically represent the **earliest point in time at which a process** becomes profitable in the best case (shaded bar), in the reference case (gray bar) and in the **worst case** (black bar). If this applies to a process in two cases at the same time (e.g. small dismantling plant in the political scenario: positive extreme case and reference case 2017), the more optimistic case is not shown. The width of a composite bar illustrates the **uncertainty** of the time-related break-even point associated with the process. Wide bars indicate a large time deviation in the achievement of break-even points between positive and negative extremes. The scenario-related differences in the position and width of the bars of a process are an indicator of the dependence of the economic efficiency of the process on the volume.

It is clear that if the "**Political**" scenario occurs, the break-even point for each process occurs at the earliest point in time and with the greatest certainty. In the "**Realistic**" scenario, on the other hand, the break-even points are reached at the latest point in time, but with less uncertainty than in the "**Pessimistic**" scenario. In the latter scenario, the uncertainty regarding the timing is greatest. For example, the time volt between the most favorable and least favorable case in the "Political" scenario for the **large dismantling plant** is 3 years; the earliest the break-even point is reached is 2018. In the "Pessimistic" scenario, it is reached in 2020 at the earliest and 2028 at the latest due to the lower dynamics and the lower level of used battery volumes, i.e. the range is 8 years. By contrast, the break-even points for **small dismantling plants** will occur much earlier and with less uncertainty in all scenarios. The situation is different in the case of small and large **processing plants**, where only minor differences can be seen. For the **hydrometallurgical treatment process**, it is clear that the break-even point is only reached in the positive extreme scenario and in the reference scenario, but not in the negative extreme scenario, if only LFP is processed during the period under consideration.

The economic efficiency of the overall process is achieved in all scenarios. Both with exclusive processing of NMC and with mixed processing of NMC and LFP, this will already be the case in 2018 or 2019 at the latest if the "Political" scenario occurs. In the "Pessimistic" scenario, the timing varies widely between 2019 and 2023 with slightly higher uncertainty in the case of NMC80:LFP20. In the "Realistic" scenario, the entire process will be profitable by 2023 at the earliest and 2026 at the latest. If only LFP is processed, the break-even point is reached one to two years later in the reference case, and between two years later in the negative extreme scenario ("Political" and "Realistic" scenarios) and four years later ("Pessimistic" scenario).

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

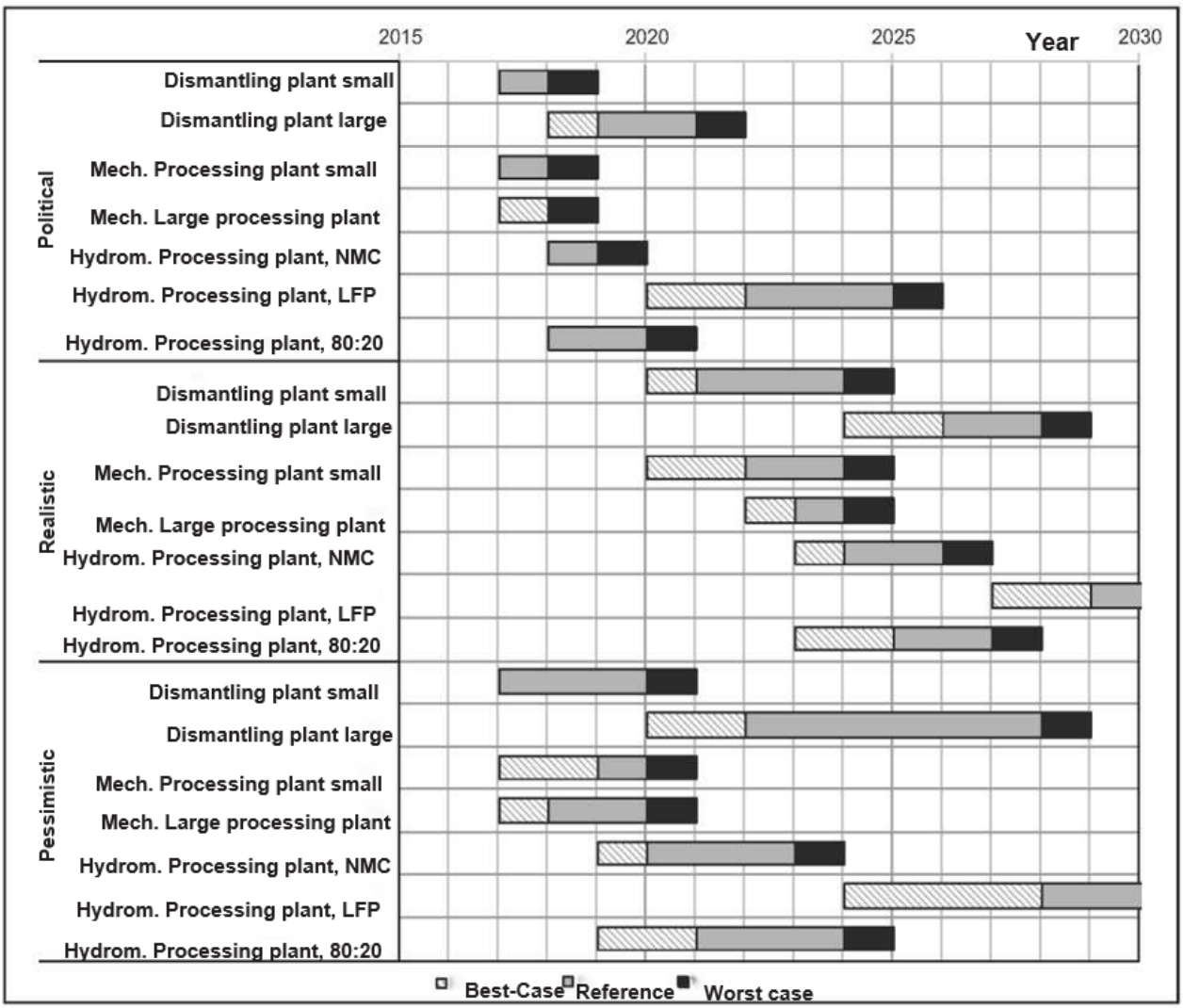


Figure E-20: Time-related break-even points of the individual processes depending on the scenarios for used battery volumes

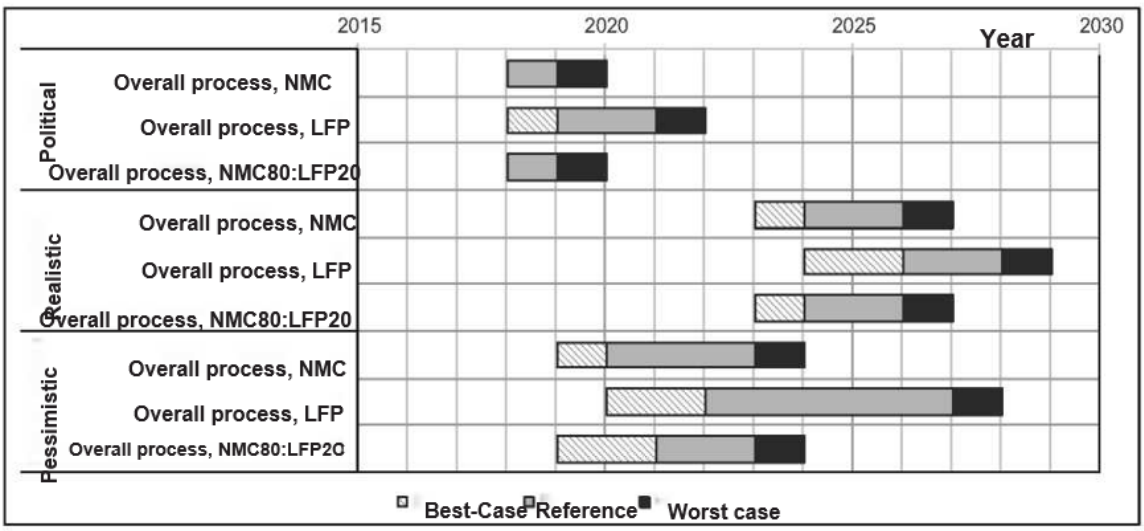


Figure E-21: Time-related break-even points of the overall processes depending on the scenarios for used battery volumes

E. 4.5 Summary

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The economic evaluation shows that the LithoRec recycling process for lithium-ion traction batteries could be operated economically from an annual volume of approx. 4.500 tonnes of systems or 15,000 BEV systems under the premises and assumptions presented.[27] Such a volume would be achieved between 2018 and 2020 if electric vehicles achieve a high market penetration and the targets of the National Development Plan for Electric Mobility are met.

The economic evaluation assumes that all processes are operated within a single company or within a perfectly cooperating supply chain of several companies, in which risk, profits and losses are distributed among each other. If the individual processes are operated by competing players, surpluses generated in dismantling, for example, would hardly be used to cover fixed costs in mechanical processing. Furthermore, the individual players would attempt to skim off profits arising in preceding or subsequent processes through their pricing policy. The economic efficiency of individual processes can be significantly impaired by certain factors. The biggest factor is falling prices for the recovered recyclable materials, but also the additional input materials required (e.g. nitrogen). Furthermore, in addition to the quantity of used batteries, their composition is a key driver of a financially self-sustaining recycling process. If lithium iron phosphate batteries are predominantly used in electric vehicles in the future, the break-even point of the overall process will only be reached at around 6.800 tonnes of systems or 21,000 BEV systems. The hydrometallurgical process would become generally unprofitable under certain circumstances.[28]

Even the small dismantling plants and small mechanical processing plants cannot be operated economically under unfavorable conditions. However, it has been shown that investing in small dismantling plants is associated with lower risk. Due to only moderate economies of scale in terms of fixed costs, the staggered construction of several small dismantling plants appears to be financially advantageous compared to the early construction of a large dismantling plant. This was also demonstrated in **AP A.3**. However, it remains to be seen whether this also applies to the mechanical processing plants, which have extreme economies of scale due to the higher degree of automation.

It was recognized at an early stage of the project that the manual sorting separation of cells under the given conditions was not only costly, but also tended to be associated with high risks for personnel. Automatic sorting separation, on the other hand, does not appear to be technically feasible due to the large number of different cell designs - in particular due to a lack of standards. Accordingly, the focus of the economic evaluation was placed on mechanically destructive separation, for which a rough concept has already been developed. Given the lack of tests of mechanical processing with regard to the recycling efficiency that can actually be achieved, the purity of some of the recovered recyclable materials and possibly other recoverable recyclable materials, the calculated process coverage contributions have so far been insufficiently substantiated to be able to derive generally valid statements. A further technical and economic investigation is strongly recommended, as the feasibility of the entire LithoRec process depends on the effectiveness and efficiency of the mechanical treatment.

The static evaluation of the individual processes and the overall processes does not allow any direct recommendations to be made as to when investments should be made in the individual processes against the background of the uncertain and possibly dynamic volume of used batteries. This should be examined in more detail using dynamic valuation methods (e.g. net present value method).

[27] In the reference case with a mixed volume of NMC80:LFP20.

[28] In the negative extreme case with high fixed costs and a low process contribution margin.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

F Development of easy-to-disassemble battery systems and life cycle-oriented safety concepts

In **PB F**, the focus of the investigation is on the design of a battery and the tools that support the description of this design.

Batteries provided by the project partners during the project period serve as the basis. Based on the investigations of these batteries in **AS F.1**, example dismantling sequences are recorded and structured with the help of a software tool. The resulting findings are part of **PB B** and are explained in more detail there.

Based on the dismantling investigations, the next step **AS F.2** attempts to identify characteristics that allow comparisons to be made and parameters to be calculated.

AS F.3 sets out design guidelines that are intended to promote the dismantling-friendly development of batteries. Rules (e.g. dismantling, safety aspects) are derived based on the requirements of the interaction between humans and the battery as well as general design considerations for dismantling. Finally, these rules are used to set up battery modules as examples, each of which covers a selection of the established rules.

As a further influencing factor, **AS F.4** takes a closer look at the vehicle installation spaces for battery integration. Together with the rules for the general structure of a battery, these form the basis for implementation in CAD. To this end, requirements are defined that are to be achieved by the CAD tool with the interaction of design tables. The actual implementation was only performed as a prototype as part of the project. Furthermore, catalogs (e.g.: joining techniques, forms of heat transfer) were set up in **AS F.4** for the rapid provision of knowledge.

In addition to the design of batteries, safety plays an important role in handling and dismantling. **AS F.5** takes a closer look at concepts for increasing safety.

AS F.6 contains proposals for implementing how battery information can be stored in the form of a recycling passport and in the IDIS information system.

F.1 Development of a tool for integrated recycling and environmental assessment of battery systems

The aim of **AS F.1** is the conception and prototypical implementation of a tool for integrated product evaluation with regard to ease of dismantling, recycling efficiency and environmental impact in the disposal of battery systems. This is based on the ProdTect software tool, which is briefly presented below.

ProdTect - a joint development of IWF-TUBS and the KERP Competence Center Electronics and Environment - is a product analysis and evaluation software that makes it possible to calculate dismantling sequences and times, achievable recycling efficiencies and resulting fractions at material level under various framework scenarios on the basis of a product model by linking it to a database with fracturing and process data [HERRMANN 2005]. In recent years, the software previously used primarily for the evaluation of electrical and electronic devices has been extended for use in the automotive sector by IWF-TUBS [RABITSCH 2005], [RABITSCH 2006], [RABITSCH 2007], [FRAD 2009], among others. By integrating the software into the LithoRec project, the basic modeling and evaluation methods are to be expanded with regard to the explicit requirements of battery recycling.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Based on the product analysis of the I+ME battery system performed by IWF-TUBS, an initial ProdTect product model of a lithium-ion battery system was created. This is a parametric model that consists of all the data required for the dismantling and recycling assessment. This includes information on the components used, the joining techniques and the product structure (priority relationships). This data was determined in the test dismantling. Figure F-1 shows the schematic structure of the model input in ProdTect using the example of the battery system provided by I+ME.

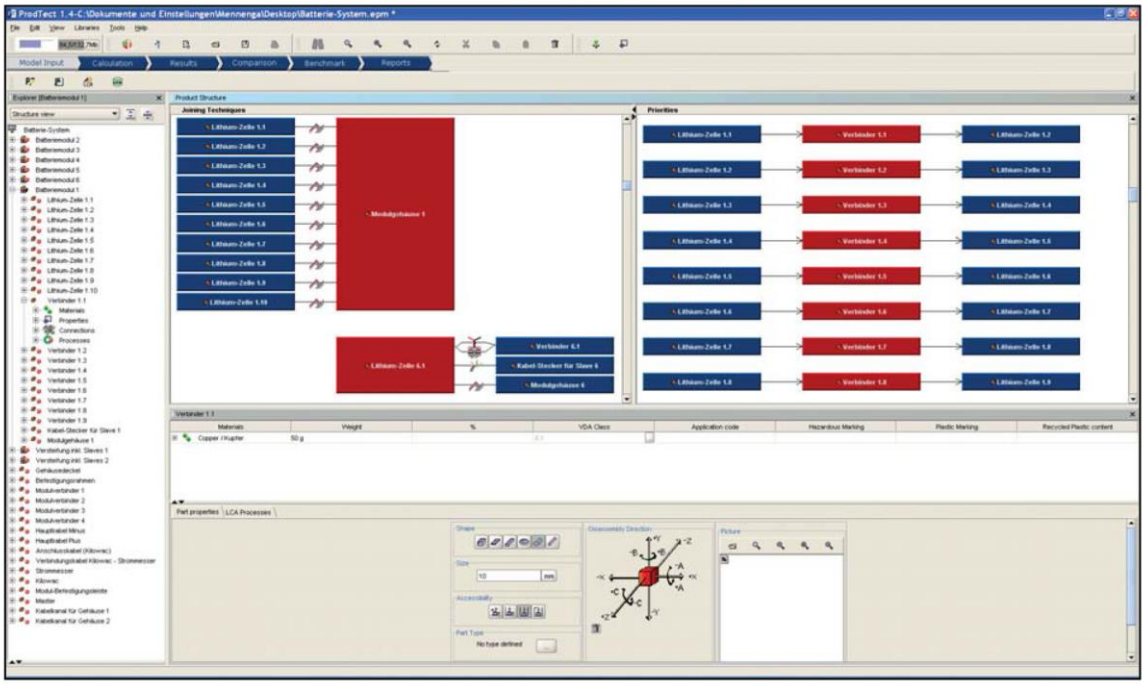


Figure F-1: Model input in ProdTect using the example of a Li-ion battery

The model input is divided into three sections:

- Component information (left bar and bottom right window) contains the material and geometry data of the battery system, i.e. the material composition of components as well as the rough shape, dimensions and the relative positioning and accessibility of a component.
- Connection techniques (upper central window) include design elements or measures that connect the various components/assemblies of the battery system with each other. The construction elements include physical joining techniques such as screws, rivets or spot welds.
- Priority relationships (upper right window) describe the hierarchy of the connected components of the battery system. These must be observed during dismantling in order to separate individual components.

During the project period, the ProdTect software was adapted to the specific conditions of battery recycling. To this end, new components and recycling processes were created in the existing databases. Figure F-2 shows the expansion of the recycling process database in ProdTect to include the recycling process for lithium cells to be developed in LithoRec. General information on the recycling process was integrated as well as achievable recycling quotas and any necessary input restrictions.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

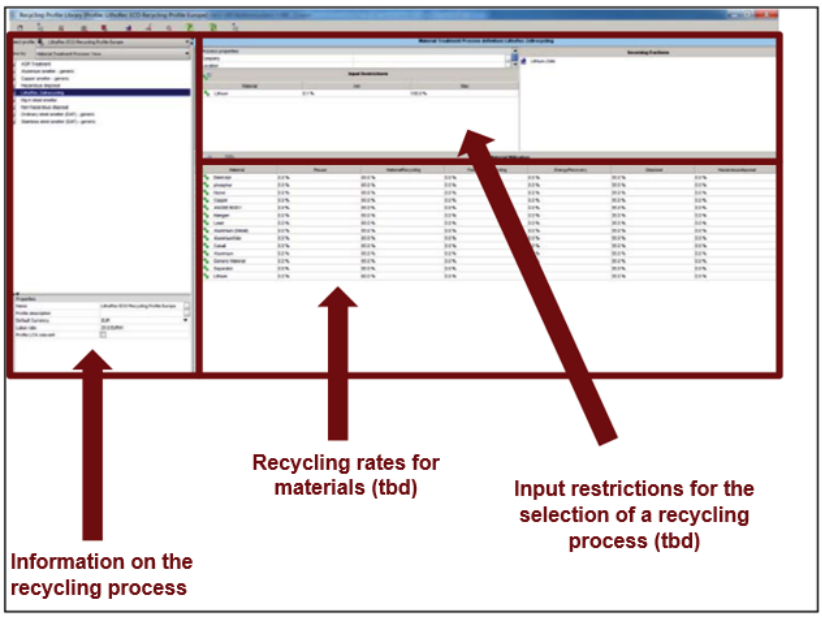


Figure F-2: Extension of the recycling database in ProdTect

It is also possible to integrate new tools into the databases to reduce dismantling times. As this must be done depending on the specific battery systems, which were not available during the project period, no further modifications were made here. This must be done in relation to standard car batteries.

Based on the product analysis performed by IWF-TUBS, a ProdTect product model was created for each of the lithium-ion battery systems provided. These are parametric models consisting of the data required for dismantling and recycling assessment. This includes information on the components used, the joining techniques and the product structure (priority relationships). The required input data was determined in the test assemblies and supplemented by material data.

Special requirements for the recycling of electronic components are required by law (Battery Ordinance) or additionally specified in various standards (VW 91100, 91102 and 91103, SN36350-1, VDA 260, etc.). Ensuring at least one communication access to the battery and the use of standard battery management systems are I+ME internal principles for providing battery information.

For series batteries, the evaluation according to ISO 22628 is recommended in order to analyze and classify lifecycle, environmental and recyclability accordingly. Figure F-3 illustrates the presentation of the results.

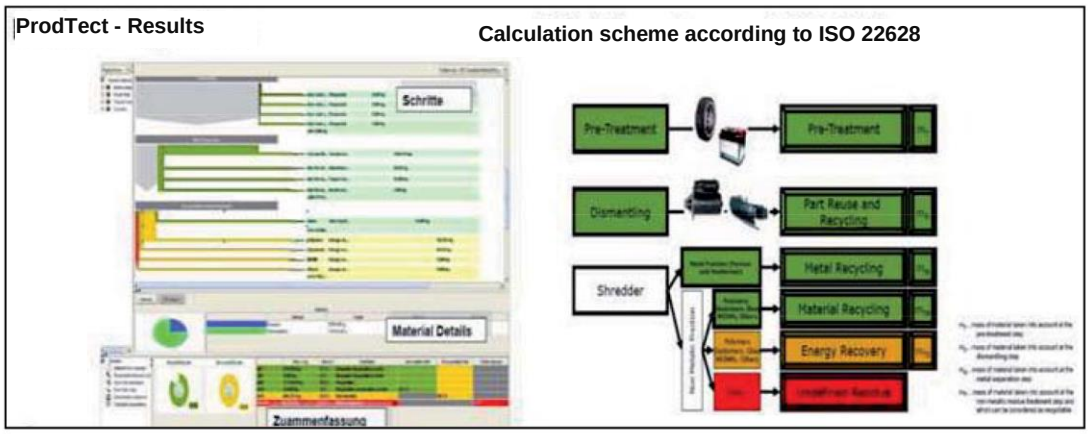


Figure F-3: ProdTect result visualization

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

F.2 Characteristic dismantling, recycling parameters and dismantling-friendly electrode design

F.2.1 Determination of a characteristic dismantling and determination of recycling parameters for representative battery construction concepts

The aim of **AS F.2** is to determine characteristic parameters for different battery concepts with regard to dismantling and recycling. The basis for this is the sensible division of different battery concepts currently in circulation. IK-TUBS performed the necessary research into the design of existing battery systems and the connection technologies used. The data collected was systematically processed and compiled in the form of design and solution catalogs. These catalogs are based on [DIN 8593]. The catalogs are discussed in more detail in **AS F.4**.

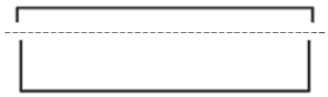
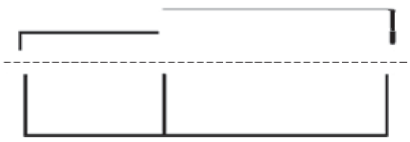
There are currently no representative, standardized battery construction concepts, only individual conceptual solutions. In particular, there is a lack of necessary standardization with regard to cell shape and size, cell connections and cell connection technologies. Dismantling times and optimum dismantling depths were therefore determined as examples for the battery systems provided. This was done on the condition that lithium cells are dismantled and run through the recycling process to be developed in *LithoRec*. The resulting dismantling times for the dismantling of all lithium cells for different battery systems can be found in the results from **AS B.1.1**. The dismantling sequences were described in the form of dismantling priority graphs. The requirements presented in **AS B.1.6** for the dismantling-friendly design of battery systems were derived from this. These form the basis for the development of conceptual proposals for a new design of lithium-ion battery systems by IK-TUBS.

With the help of the product analysis of the battery systems of the project partners I+ME and Audi performed in **AP B.1**, general dismantling steps can be derived. These steps form a basic framework that can be expanded through provider-specific components to cover all batteries. Using this example assembly, the necessary tools for constructive support can be developed later on.

The aim of dismantling is to be able to remove the cells from the battery. The dismantling steps are briefly described below.

The removed battery may be equipped with a cooling system, which means that the first step is to check whether the cooling medium is prevented from escaping. Normally, however, safety should have been restored after removal. The first correct dismantling step is therefore to open the battery housing. In the simplest case, the battery housing only consists of a trough that is closed with a cover. However, a battery can also have several housing compartments and corresponding covers (see Table F-1) that separate the individual components. This may mean that the housing opening step has to be performed more frequently.

Table F-1: different options for housing division

Number of housing divisions		
	Simple housing division	Two-part housing cover

The next step in the dismantling process is to disconnect the electrical contacts. This includes the connections between the modules, the connection to the high-voltage relay and the contact points of

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

the BMS, provided the latter is integrated in the battery housing and is not connected to the battery externally.

Once all relevant electrical contacts have been disconnected, the modules can be removed and dismantled separately. If the module is to be disassembled further, the following steps must be repeated:

- Opening the housing
- Disconnecting the electrical contacts
- Removal of the energy storage unit

As an additional element, the module can contain a slave that monitors the cells through additional connections. These additional cables must be removed together with the connections between the cells so that the cells can then be removed.

The more work steps are required, the more extensive the entire dismantling process becomes. If the individual work steps differ greatly from one another, the complexity of the dismantling process also increases. This can be caused by different joining processes, for example. This means that additional dismantling tools or dismantling directions for the tools are required.

Basic considerations for recycling the lithium-ion battery

For the lithium-ion battery, the term recycling can be divided into the areas of product recycling and material recycling. Both areas require different solutions. There is both product recycling and material recycling.

As the name suggests, the aim of product recycling is to reuse components after recycling. In material recycling, on the other hand, the component condition is irrelevant as long as the materials of interest can be recovered in further processing steps.

If the aim is simply to get at the cells in order to recover materials from them, then pure material recycling is a good option. Only if other components of the battery are to be removed for later use when the battery is intact must a closer look be taken at the connection types.

Dismantling plays an important role in assessing the recyclability of a product, but there are also other factors such as the choice of materials.

A choice of material must be made for each battery assembly. A material composite can also be created for an assembly. However, the various metals and plastics that can be used in construction require different recycling processes, so that material purity should be aimed for in an assembly. If this is not possible, the connection types should be selected in such a way that the connection can be easily disconnected. Otherwise, more complex recycling processes must be used. Furthermore, liquids/gases that are hazardous to humans should be avoided. If their use cannot be avoided, the easy discharge of hazardous substances must be ensured by design.

The choice of material cannot be evaluated directly. Only in conjunction with the assembly and the task to be performed can an objective assessment be made in relation to the design alternatives.

For this reason, the following section focuses on the dismantling itself. Dismantling is largely defined by the necessary work steps. The tools, the required activities and the working time are stored in a work step itself.

To evaluate a battery, the individual dismantling steps must be examined more closely and analyzed

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

for potential with regard to other processes. If there are a large number of work steps or very time-consuming steps, the next step is to go into the exact activity during this step. Design measures for improving the ease of dismantling are dealt with in **AS F.4**.

If all steps are worked through, the battery concept under investigation has been optimized. The sum of the work steps (number and time) enables an initial estimable comparison between different battery systems.

F.2.2 Determining a design for electrodes that is easy to dismantle

In addition to the discussion of battery systems designed for easy dismantling, cells and their components must also be integrated into this consideration. The aim of **AS F.2.b** was to investigate whether and how an easy-to-dismantle electrode design can be realized. The aim of this work step was therefore to improve the recyclability of the active materials bound to the current collector by changing the formulation without impairing the performance of the original electrodes. This work step is largely to be regarded as separate, as the focus is not on design but on electrode production and formulation.

From **AS B.3.3** and **AS B.3.4**, no specific requirements could be formulated for the electrodes from the point of view of recycling or any difficulties arising during the dismantling of the current electrodes, except for the fact that good adhesion of the coating to the current collector makes reprocessing more difficult. On the other hand, binder residues can lead to altered particle surfaces vs. altered material properties, which has an impact on the final quality and reusability of the recycled materials.

However, this reduced adhesive strength, which is desirable from a recycling perspective, is at odds with the high adhesive strength required for the high mechanical and electrochemical demands on cell performance during cell life, especially for the extremely demanding and durable cells for automotive applications.

During the second half of 2010, in parallel and independently of this project, LTA came to the clear conclusion that a reduced adhesive strength of the electrode coating is not acceptable under any circumstances in cells for long-life applications.

This has removed the basis for the originally planned work step. Consequently, we have decided not to process this AS any further. Rather, recycling processes must be developed in such a way that electrodes with excellent adhesion can be processed.

As the content of this AS can largely be regarded as separate from all other work steps in **PB F**, none of the project objectives are affected.

F.3 Development of design and construction guidelines for the dismantling-friendly development/production of batteries

As a result of I+ME's analyses, there are different processes for battery construction orders - depending on whether prototype or redesign vs. series product production is required. The scope of the design requirements and the standards to be taken into account are usually described in the client's specifications, which often run to more than 200 pages. Frequently mentioned standards are listed below:

Environment and operating conditions

Standard	Title
EN 50125-1: 1999-09	Railroad applications - Environmental conditions for equipment - Part 1: Equipment

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

	on railroad vehicles
EN 60721-3-1: 1997-03	Classification of environmental conditions - Classes of environmental parameters and their limit values - Long-term storage
EN 60721-3-2: 1997-03	Classification of environmental conditions - Classes of environmental parameters and their limit values - Transportation
EN 60721-3-5: 1997-04	Classification of environmental conditions - Classes of environmental parameters and their limit values - Use on and in land vehicles

Environmental requirements

SN 36350-1:2006-10	Environmentally compatible products: Part 1: Guidelines for product design
SN 36350-2:2006-10	Environmentally compatible products: Part 2: Hazardous Substances, Prohibited List, Avoidance List
SN 36350-5:2006-05	Environmentally compatible products; Part 5: Ecological requirements for packaging
SN 36350-6:2006-08	Environmentally compatible products; Part 6: Recording of substances in products
SN 36350-7:2003-03	Environmentally compatible products; Part 7: Product environmental declaration
SN 36351:2001-04	Regulations on placing hazardous substances in products on the market

Battery construction requirements

Battery products must be designed with the lowest possible environmental impact during manufacture and operation in mind. A recycling-friendly design should be aimed for. The materials used should be labeled as far as possible and appropriate. The design of the product must comply with the legal regulations in the field of environmental protection for its operation, maintenance and disposal (recycling, disposal). The materials used, their components and compounds must be selected as follows:

- Lowest possible pollutant content
- Durable products/materials
- Reusable or recyclable materials
- As few varieties as possible

In this context, particular reference is made to SN 36350-1, in which key aspects are discussed in detail. Basically, all batteries have a similar basic structure, which is shown in simplified form in Figure F-4 below.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

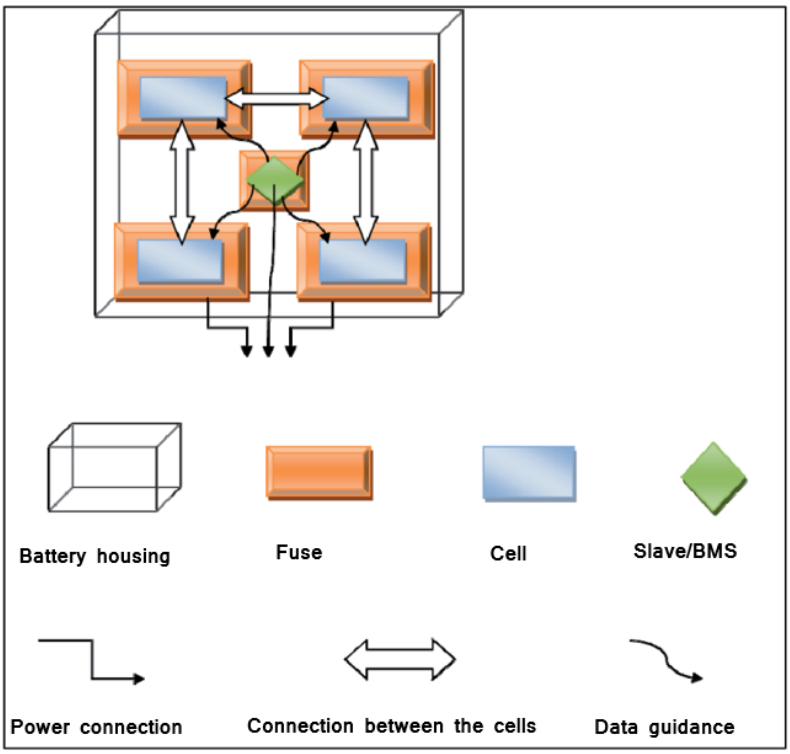


Figure F-4: Complete battery system with all necessary components

Among other things, the following analyses were performed on the dismantling-friendly design of battery systems:

- Investigation of the advantages and disadvantages of various options for securely sealing a battery system (welding, gluing, riveting, bolting) with regard to production, operation, maintenance and dismantling of the system.
- Design of the battery housing and the arrangement of the components it contains
- Concepts for easy-dismantling battery module design

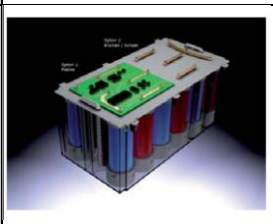
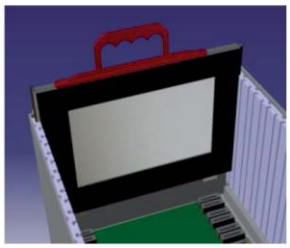
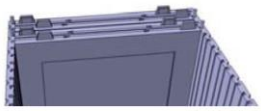
The results were stored in tables for quick access. At Volkswagen, a wide variety of approaches to the dismantling-friendly design of battery systems were discussed and analyzed. However, it turned out that in the current state of development of Li-ion battery systems, binding design guidelines are not necessarily expedient: The technology of automotive Li-ion batteries is still very new and the possibilities for designing the systems are correspondingly diverse. The current focus is on the demanding challenges of safety, reliability and cost reduction (through efficient assembly). During the project, it became clear that these aspects can conflict with the goal of ease of dismantling. For example, plug-in connections of modules or cells could make dismantling easier, but in terms of low susceptibility to faults and therefore reliability and durability, fixed (screw) connections currently appear to be the best option.

The aspects of safety, reliability and costs must be given top priority in the short term in order to be able to implement electromobility in series production - at acceptable prices for the customer. Focusing on ease of dismantling at a later point in time when the technology is more mature is also justifiable because the expected sales figures for electric vehicles will only account for a small market share in the short to medium term, and a higher dismantling effort is more justifiable for only a few vehicles.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Nevertheless, it is planned to consider the concepts developed in the development of future battery systems and to implement them if necessary. These objectives are generally supported by the efforts to ensure low service costs for any repairs. However, as described above, it does not seem sensible to restrict the freedom of action in the design process in the search for the best solution by means of fixed dismantling guidelines.

Table F-2: Concepts of easy-to-dismantle battery module design

Variant	Round cells	Pouch cells	Pouch cells
Aspects considered	- The battery is made up of standard modules that can be combined in any number - There is a standardized mounting direction for assembling the modules. In this example, the direction is vertical from above. - The cells are electrically connected to each other through a detachable connection.	- Protection of the “soft” cells during assembly/dismantling through a frame structure. - Simplification of the electronics through implementation in the form of a circuit board - Simple assembly/dismantling with tools - There is a standardized mounting direction for assembling the modules. In this example, the direction is vertical from above.	- Separation of cells and electronics - Cable reduction - Easily detachable cell connection - Special gripping surfaces for handling the modules
CAD Model		 	

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

F.4 Development of tools (CAD tools, K. catalogs...) for the design and simulation of overall battery concepts, taking into account the mutual influences of battery, peripherals and vehicle technology

The aim of this step is to provide tools that provide targeted support during the development process. The focus is initially on the collection of knowledge in the form of catalogs. As a knowledge repository, the data is compactly arranged in them and allows quick access to the stored information. In a further step, the extent to which the content can be implemented in the form of CAD models/applications is then examined.

Catalogs

The structure of catalogs can have different characteristics, but the general structure is the same in all catalogs. As illustrated in Figure F-5, the catalog can be divided into the structure and access features and the information section.

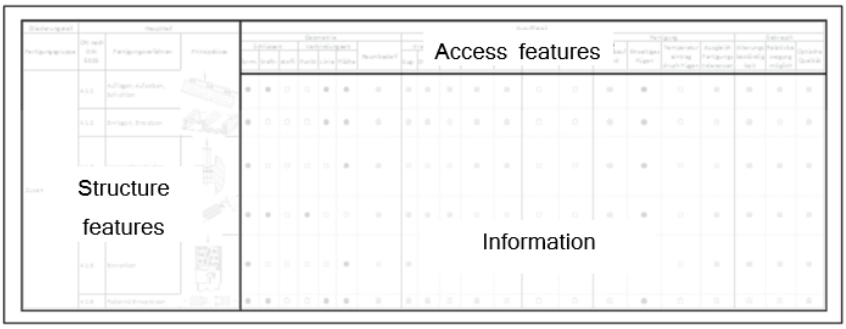


Figure F-5: Structure of a design catalog

Two main aspects have crystallized in the considerations for dismantling a battery. These are, on the one hand, the joining processes, both for the cells and for cell contacting, and on the other hand, the type of cooling that is used in a battery.

Overview of the catalogs on display

- Connection techniques based on DIN 8593
- Joining bodies
- Forms of heat transfer based on the VDI Heat Atlas

There are different degrees of information content within the respective catalogs. These always depend on the type of access features. Most of the information fields have a rating for the corresponding classification attribute in comparison to the other attributes.

Based on the evaluation, good solutions can be worked out that can be applied to the design of batteries. This solution is implemented in **AS F.3**.

Implementation of a CAD tool

Catalogs can be a great help for the design of batteries as they contain the necessary knowledge in a bundled form. The disadvantage is that the construction still has to be done by hand.

The creation of a parametric CAD model requires a precise analysis of the necessary requirements. The use at the beginning of the development process forces you to limit yourself to the most important variables. Here it is not yet decisive how the later construction is designed, whereby many components can be simplified using placeholders.

The clean CAD implementation of the dependencies between vehicle and battery are so extensive

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

that the implementation far exceeded the time frame of the project. For this reason, the step was pursued to identify approaches for modeling that can be meaningfully implemented with a greater research effort.

The following section presents a selection of input variables that proved necessary during the development process:

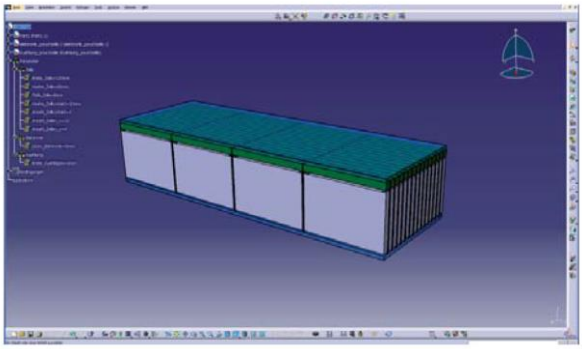
The installation space in the vehicle	In principle, there are 63 possible installation space variations. However, they can be specifically limited by the battery removal methods addressed in work **package A3**
The wiring strategies	Series connection/parallel connection/combination of R and P connection
The shape and dimensions of the cells	DIN SPEC 91252 simplifies the dimensions. However, as soon as the cell manufacturer's own dimensions are used, the variety increases enormously
The design of the battery housing/modules	
The required performance data	
The type of cooling with the connection conditions in the vehicle	

Approaches for the solution

- Consideration of the variation of cell dimensions and cell orientation in space
    - There is a dependency between the alignment of the cells in the room and the size (height) of the installation space. Another factor that plays a role is the wiring strategy.
- The type of cooling systems must be integrated into the module volume as a surcharge as well as into the total volume of the battery as an extra assembly.
- The installation space in the vehicle is not a simple body that can be automatically filled with cells. To do this, the identified installation space must be converted into practical basic bodies. The number and size of the newly created bodies have a significant influence on the subsequent result. To reduce this influence, it should be possible to exceed the installation space in all 3 spatial coordinate directions.
- Surcharges for the electronics and housing
- Control of the geometry through connected design tables.

Table F-3: Representation for implementation in CAD

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

	Templates are used to store the basic geometry of the cells in the CAD program. The orientation of the cells in the module/in the overall battery is predefined using pattern functions. The electronics are given an installation space controlled by parameters. If the position of the contacts changes, the number and position of the geometry adapt. Similar to the surcharge for the electronics, the surcharge for the cooling also changes depending on the cell contacts

The following table F-4 shows how the different degrees of electrification can be covered with two different basic modules (18 V and 36 V).

Table F-4: Minimum number of modules

Degree of electrification		Mild hybrid	Full hybrid	Plug-In Hybrid	Electric vehicle
Tension		40 -150 V	200 - 400 V	200 - 400 V	300 - 400 V
Minimum number of modules	5 x 3.6V (18 V)	2 - 3	11 - 12	11 - 12	16 - 17
	10 x 3.6V (36 V)	1 - 2	6	6	8 - 9

If there were several standardized module dimensions or defined package dimensions for the vehicles, similar to the cells, templates could be stored in the CAD model that could cover all the vehicle variants to be generated.

F.5 Derivation of life cycle-oriented safety concepts, especially for dismantling, dismantling and recycling of lithium-ion batteries

In collaboration with the LithoRec cooperation partner AUDI, a concept (initially internal to Volkswagen) for safe handling when working with high-voltage components was developed based on the processing of **AS A.2.1** - in particular the existing safety rules and regulations cited in the report.

Practical experience in dismantling traction batteries of various electric vehicle concepts (EV, HEV ...) together with the respective battery developers has provided important information for working on open battery systems. These concern, for example

- Necessary training for the respective work step
- Indication of particular hazard potential
- Tool to be used (e.g. insulation regulations for the tool)
- Sequence of work steps that must be followed
- Storage instructions for the dismantled modules/cells

These instructions are revised in accordance with internal agreements and on a battery-specific

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

basis.

If security concepts are to be created, they must fulfill various requirements.

- They should be kept as simple as possible so that they can be used anywhere, even by less qualified personnel. (Protection against misuse)
- They should provide sufficient information to ensure correct handling.

The two requirements are in opposition to each other. On the one hand, it should contain a lot of information, but on the other hand, workers who have little knowledge of the battery should still be able to handle it correctly. This means that there must be different levels of safety concepts that are applied depending on the place of dismantling (small workshop, recycling center, battery manufacturer, ...).

When installed, the BMS monitors the battery and informs the vehicle user of any faults. People can only come into regular contact with the battery again from the workshop onwards. An exception is a crash between vehicles, in which the batteries involved are damaged and can be openly accessible to rescue services.

This means that the safety concepts must be able to safely handle both alternatives (undamaged battery and damaged battery). It is important for the further approaches that transportation has a lower hazard potential than active manual work on the battery. The approaches for life cycle-oriented safety concepts are based on this process and are divided into the following areas.

- Transportation
- Dismantling

The term “transportation” refers to the entire handling of a complete battery. In addition to the actual transportation, this also includes the handling up to the actual installation and after removal.

Dismantling” includes all steps associated with dismantling the battery.

Transportation

A fully assembled battery has only a few contact surfaces on the outside; in addition to the housing, these are the electrical connections for the data and power, as well as the connection for a possible cooling system. For the transportation itself, it is therefore only necessary to ensure that the worker does not come into contact with the connections and that he is protected if the housing is energized (damaged battery). The contents of the battery are not considered further if the battery is undamaged. If the battery is damaged, the safety concepts for dismantling apply.

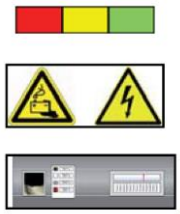
- Covers for the connections
- Insulation of the housing to the live electronics
- Insulated gripping surfaces
- Safety switch

Dismantling

Before starting to dismantle the battery, the worker must obtain information about the battery. Only then can he safely proceed with dismantling. There are several solutions for making this information available to the worker. The solutions shown in Table F-5 have varying degrees of complexity and cannot be used by just any worker.

Table F-5: Different reference options

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Visual cues	Color coding (Warning) symbols Integrated displays (sight glass/pressure indicator)	
	Voltage measurement	
Reading out information with tools	Readout interface for the BMS data Coding of information	

F.6 Development of (minimum) documentation standards for proper treatment, dismantling, dismantling and recycling

There are already several regulations that must be applied when handling battery systems. On the one hand, there are regulations for batteries, including the DIN V VDE V0510-11 preliminary standard Safety requirements for lithium secondary batteries for hybrid vehicles and mobile applications, DIN VDE 0510 Part 3 for batteries in electric vehicles. The VDE and ZVEI are also working on further standards, guidelines and recommendations. Furthermore, according to EN 50153, at least the following safety symbols should be affixed:

- High-voltage arrow
- Dangerous residual voltage after switching off,
- Explosive gases
- Corrosive liquids (if applicable).

The safety signs and warning notices must be abrasion-resistant and as weatherproof as possible.

Another point is the instructions for use and handling. These must contain appropriate details on the dismantling, servicing and removal of the battery systems.

To increase the safety of series batteries, risk assessments (FMEA) and ISO 22628 evaluations should always be performed for them.

Possible tools for documenting dismantling and recycling information are the recycling passport and the International Dismantling Information System (IDIS). These offer the possibility of displaying various dismantling and recycling-relevant information about a product.

The recycling passport was published in the form of a Publicly Available Specification (PAS) as PAS 1049 “Transmission of recycling-relevant product information between manufacturers and recycling companies - The recycling passport” in 2004. In addition to AIP-TUBS and IWF-TUBS, the authors are the companies EC, Agfa-Gevaert AG and LCE Consulting GmbH.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

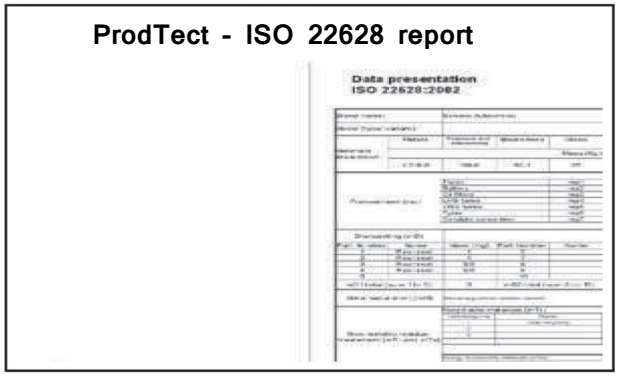


Figure F-6: Example of the valuation option

In detail, the recycling pass is structured as follows:

- Details of the product manufacturer
- Product identification
- Product-related recycling properties
- Directives, laws and standards taken into account
- Information on the substances and components that must be removed and processed separately
- Substances and components requiring special attention
- Recycling data
- Change history
- Variants (optional)

The **IDIS** (International Dismantling Information System) is currently the most important international platform for providing information (primarily) to ELV treatment facilities. In addition, the car manufacturers fulfill their statutory information obligations to provide recycler information. The information is provided by car manufacturers from Europe, the USA, Japan, Korea and Malaysia, coordinated in the IDIS consortium, entered into the database system and regularly updated.

Proposals for the documentation of dismantling and recycling information for the presentation of manufacturer-related information on HV batteries in IDIS

Since the introduction of European end-of-life vehicle legislation, the IDIS has established itself worldwide as a useful and efficient medium for documenting safety and environmentally relevant components in vehicles. The additional use of the recycling passport for individual vehicle components is seen by car manufacturers as an unnecessary additional expense, as the information contained in the recycling passport is already available in the IDIS and is regularly updated. Among other things, information on the manufacturer and the product as well as details of the components and materials contained can be called up here with information on the separate treatment of certain materials. In addition to indicating which valuable and hazardous substances are contained, information is also provided on where these materials and components are located in the vehicle. Illustrations such as exploded views are used for visualization.

The information is already provided with a high degree of standardization as general or

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

manufacturer-specific information in 30 different languages. This means that in future, all product-related data on HV traction batteries relating to the recycling process can also be provided by car manufacturers through IDIS.

As already described in **AS A.2.5**, parties downstream of the end-of-life vehicle recycler in the recycling process can also be provided with important information on cell chemistry through corresponding markings on the battery systems simply and inexpensively without major coordination effort. Object-related information (e.g. load status) can also be determined by the process participants using appropriate inspection equipment if required.

As part of the project, several variants for the documentation of HV traction batteries were tested. In conclusion, the investigation into the implementation in IDIS revealed the following points:

1. The manufacturer- and vehicle-specific information can be easily displayed both as an additional PDF document and in an interactive, self-explanatory sequence of images using the existing IDIS functionality.
2. It is recommended that the possibility of interactive presentation be created or used, as this enables a precise and clear presentation for future (e.g. future) projects. fully electric vehicles).
3. Object-related information, such as battery condition and history, cannot be meaningfully integrated into the IDIS, but should be recorded and stored at this point in the process sequence due to its usefulness as a decision criterion for further handling of the removed HV battery (reuse/repair/recycling).
4. Information on the transportation and storage of HV traction batteries must be made available to the recycler in a suitable form (either in the general safety documents in the IDIS or as a supplement in the on-board literature).

Figure F-7: Examples of feasibility in IDIS

G Conceptual design of a recycling pilot plant

In **PB G**, a possible recycling pilot plant was conceptualized, which was put together from the individual steps of the previous project areas. The entire facility is a new design, i.e. no existing facility is being converted or extended, but a completely new facility is being built on a greenfield site.

In order to be able to design the overall system, the following framework conditions had to be defined for the design of the system:

- Processing capacity of 700 kg cell mass per hour
- Single-shift operation
- Battery types to be processed are Li-ion accumulators in the form of traction batteries, hybrid batteries and plug-in batteries

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- No thermal treatment of the accumulator cells is planned

Unloading is performed in a two-stage process. In the first step, the battery systems are discharged in the storage area within the rack storage facility to the extent permitted by the battery management system to prevent damage to the cells. After the battery cells have been removed from the modules, the second step of discharging takes place. This takes place at the dismantling site and results in the battery cells being deeply discharged. The dismantling of the battery system follows the primary goal of freeing the cells for further processing. Other recyclable materials, such as copper cables and circuit boards, are also collected as separate fractions for further recycling. This is followed by mechanical comminution and separation of the cell and preparation of the active material.

The facility is spatially divided into three sections. In the first section, the warehouse, the incoming batteries are temporarily stored and an initial discharge takes place. The second section comprises the dismantling area, where the battery systems are dismantled manually. In addition, the removed battery cells are deep discharged in this area. The third section is mechanical cell preparation. The cells are crushed and the active materials separated in various mechanical steps.

G.1 Discharging the batteries and dismantling the system components

Dismantling and processing of the batteries and cells are described and accounted for in the previous **AP A.4** and **AP B.1.**

The processing tests at Electrocycling serve as the basis for the design of the pilot plant.

Basic discharge of the batteries

The lithium-ion traction batteries are discharged in a two-stage process. In the warehouse, the batteries are connected to a central electrical discharge system for basic discharging of the batteries. Discharging batteries is only possible to a limited extent and not until they are completely discharged. For this reason, residual loads must always be taken into account in the subsequent process steps and the work must be performed in compliance with the safety regulations. This applies to the dismantling of the operating system as well as to the preparation/dismantling of the cells.

Dismantling and electrical deep discharge

The discharged batteries are dismantled at separate dismantling points. In addition to the actual dismantling sites, areas are required for logistics, operation, the supply of batteries and storage areas for the collection of dismantled materials and their removal.

Due to the large number of products produced (steel, non-ferrous metals, plastics, electronic scrap, residual waste), a pallet system is preferred to belt transportation. Only the dismantled cells are transported on a roller rack in suitable containers for deep discharge.

The time required for dismantling and discharging the batteries is assumed to be two hours each, including the associated set-up times. The cost is based on the exclusive use of large traction batteries, as it will be reduced for smaller batteries, but then only smaller cell masses can be obtained, so the specific cost increases. One large or two small traction or hybrid batteries can then be dismantled at a dismantling station.

The size of the station then depends on the size of the traction batteries. A base area of 4.0 m x 5.0 m is assumed (unloading plus dismantling area).

Based on the necessary dismantling and unloading time, 16 stations are planned. The distribution of

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

the dismantling stations among the battery types can be seen in Table G-1. Two additional stations are provided here as a reserve. The dismantling stations are similarly equipped with tools for opening the housing, removing the cooling and control unit and removing the cells. All dismantling stations are equipped with small lifting gear for handling the batteries and dismantling parts.

Table G-1: Calculation of requirements for cutting and unloading stations

Battery type	Traction, large	Traction, small	Hybrid	Total
Discharge time/min	110	110	110	
Dismantling time	1.5 hrs.	1 hr.	1 hr.	
Labor for dismantling	2	1	1	
Set-up times	0.5 hrs.	0.5 hrs	0.5 hrs	
Cycle time	2.1 hrs.	1.6 hrs	1.6 hrs	
Batteries/day per station	4	5	5	
Cell mass/day per station	500 kg	300	200	
Number of stations	8	4	2	
Cell mass/day	4,000 kg	1,200 kg	400 kg	**5,600 kg**

All parts produced during dismantling, such as housings, control units, cooling units and sealing material, are collected in mesh box pallets. The preparation of these materials is not the subject of this study. These materials are sent for external recycling. Necessary facilities for shipping are provided in the storage area.

The dismantled cells are stored in packages weighing up to 15 kg each in transport containers (filling weight 700 kg). The containers are transported by forklift truck to an interim storage facility, from where the dismantled and fully discharged batteries are sent for mechanical processing.

The building with 16 dismantling and unloading bays has a floor area of 882 m^2 and an enclosed space of 6,200 m^3. It is a steel construction with insulated wall elements and no windows. Sufficient general lighting and appropriate workplace lighting are provided. The heating must be designed for a room temperature of 18°C.

Due to exclusively mechanical work processes, the release of electrolytes is not to be expected, which is why ventilation is not necessary.

G.2 Separation of active materials

Characterization of the material to be processed

It is assumed that mainly round cells with a metallic housing will be processed. Flat cells without a metal housing are easier to process and therefore do not need to be considered separately.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

According to our own research, the average composition of currently manufactured round cells can be assumed to be as follows:

Table G-2: Average composition of lithium-ion battery cells

Component	Mass fraction
Cathode material	25%
Anode material	17%
Electrolyte	10%
Cu electrode	14%
Al electrode	5%
Separator	4%
Housing	23%
Collector/Insulation/Adhesive	1%

The main mass flows for the treatment can be estimated from this:

Table G-3: Distribution of significant mass flows for the preparation of 700 kg of cell mass per hour

Material flow	Mass fraction	Mass flow in kg/h
Active mass (powder)	42 %	296
Electrolyte	11 %	74
Housing	23 %	164
Foils and miscellaneous	24 %	166
Total	**100 %**	**700**

Mechanical preparation of the cells

- Material task

The material is transported from the unloading station to the pre-shredder through an intermittent belt conveyor (3.01). The dismantled and deep-discharged cells are manually loaded onto the belt conveyor in the designated 15 kg batches. In order to overcome the height required for the feed to the pre-shredder, the belt should be designed as a long pocket belt, whereby one pocket must hold the batch quantity for one feeding cycle. This would allow the belt to move pocket by pocket.

Specifications for preparation:

- Packages consisting of several round <u>or</u> flat cells up to a maximum unit weight of 15 kg
- Round and flat cells are <u>processed</u> separately (with/without steel housing)
- Target throughput 700 kg/h
- Clocked extraction for pre-shredding (1 cell packet at a time; 1 to 2 cell packets per minute)

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

- Machine selection Pre-shredding

The Li-ion batteries currently on the market use various mixtures of solvents as electrolytes, which are flammable even at room temperature and form explosive vapor mixtures. Under certain circumstances, mechanical stress and/or short circuits occurring in the cells can trigger an exothermic reaction of the active mass, which takes place with the release of oxygen. As no thermal pre-treatment (pyrolysis) is performed prior to processing, pulping must be performed under inert conditions.

In principle, various types of shredding machines that have become established in the field of shredding metallic secondary raw materials can be used for pre-shredding. Slow or high-speed rotor shredders (e.g. hammer shredders) or the so-called cross-flow shredders - QZ - appear to be suitable.

The pre-shredding should cause the cell housings (sheet steel, sheet aluminum or foil) to break open and ideally already lead to an extensive separation of the active mass from the arrester foils.

With conventional rotor rippers, the degree of digestion can only be influenced by selecting a suitable grate that limits the size of the discharge unit. However, the grate gap width is limited downwards by the dimensions of the largest non-crushable components in the accumulator. Whereas conventional rotor shredders only work continuously in a throughput, the cross-flow shredders are operated in sets. This batch operation allows the duration and intensity of the load (rotor speed) to be optimally adapted to the desired degree of digestion. While slow-running rotor shredders tend to produce coarse, poorly broken down shredded products, it can be assumed that fast-running machines will deliver well broken down products.

The choice of a suitable pre-shredding unit fell on a MEWA QZ1200 cross-flow shredder, taking into account the above criteria. Another advantage of the QZ is that it is very easy to operate under inert conditions thanks to its completely closed process chamber. Cross-flow flakers from MEWA are already in use in various recycling applications, also with a closed nitrogen circuit.

Whether the QZ will be able to open all future types of battery cells (e.g. stainless steel sheet housings > 1 mm sheet thickness - GAIA cells) must be tested in detail. For planning based on the current state of knowledge, it seems irrelevant which machine is used as the basis for planning.

- Machine selection Drying

The electrolytes need to be evaporated for the subsequent dry treatment processes, which are primarily aimed at extracting the active mass. On the one hand, this step eliminates the potential hazard of flammable solvents and, on the other hand, converts the active mass into the dry powder form required for dry processing.

Convection dryers are used for drying, as they provide the best drying result for the very inhomogeneous composition of the material. There is also the question of whether drying should also take place in a batch or continuously. As some of the liquids to be vaporized are highly flammable solvents, the drying temperature should probably be severely restricted. This in turn speaks in favor of drying under vacuum, as the drying temperature can be kept low.

As there is currently no reliable data on the substances contained in the battery cells that would allow drying to be reliably designed, only a rough estimate of drying can be made at this point. The manufacturers of drying systems could not be persuaded to submit an offer under the given circumstances. It is assumed that the necessary process steps (inerting, filling, drying, emptying) of a discontinuously operating dryer require a longer work cycle in total than the pre-shredder. For this reason, batch drying is not used.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The liquid to be evaporated is mainly bound to the active mass to be separated, which in turn adheres more or less strongly to the arrester foils (copper or aluminum foils). It would therefore be advantageous if the drying process is accompanied by mechanical stress on the dried material. Fluidized-bed dryers are very suitable for intensive drying. However, since the material to be dried is a very inhomogeneous material with a very wide range of unit sizes (from coarse metal parts to fine powder), only dryers that can ensure material transport by exciting the flow bottom are suitable. The choice of dryer should therefore be a vibratory fluidized bed dryer. In addition to effective drying, the vibration will also contribute to further rubbing of the active mass from the films.

Drying must take place in a protective gas atmosphere (nitrogen), just like the crushing process beforehand. The dryer gases are circulated in a closed circuit and cleaned using a filter and condenser.

- Process description of pre-shredding and drying

The intermittent conveyor belt discharges directly into the inlet sluice (3.03) (shaft with two slides or flaps), which is open on the inlet side and closes the cross-flow flaker gas-tight to the outside. After closing, the airlock is inerted with nitrogen. By opening the airlock on the discharge side, the cell packs fall into the inertized cross-flow flaker - QZ - (3.04), where they are coarsely digested for a predetermined loading period with a loading intensity that is optimally adapted to the respective cell type.

At the end of the loading period, the QZ is emptied through a flap into a buffer container (3.05), from which the shredded material is fed through a rotary valve (3.06) through a tubular screw conveyor (3.07) to the dryer (3.08). The QZ is then flushed with nitrogen and inerted.

The nitrogen required for inerting the system is stored in liquid form in external storage tanks (3.02) (rental) and prepared for the system as required through an evaporator (3.02) (rental). It is planned to combine the drying gas of the dryer and the purge gas of the pre-shredder in a common gas circuit, the nitrogen circuit, as both units require gas circuits with a comparable structure. The inert gas circuit works as follows.

While the nitrogen is used in its initial state in the pre-shredder with its auxiliary units, it must be heated to the specified maximum permissible dry gas temperature for the dryer through a gas heater. Both the nitrogen from the pre-comminution and that from the dryer are loaded with solid particles and solvent vapors. The nitrogen to be circulated is freed from the solids through a jet filter and then passed through a condenser in which the solvents contained are separated. The condenser can be cooled using either nitrogen or cold water (1 - 5°C). As oxygen ingress occurs in the system components due to leaks that cannot be ruled out, a continuous oxygen content measurement is performed before the gas flow is fed back into the gas circuit, which is used to regulate the feed of fresh nitrogen into the system. In order to ensure the negative pressure in the gas circuit at all times, a partial quantity of gas must be discharged from the system into the environment. Due to the solvent residues it contains, the discharged gas must be cleaned using an activated carbon filter (3.09) before it can be released into the atmosphere.

The electrolyte mixtures obtained in the condenser are filled into drums, weighed and palletized using a drum filling station (3.10). The dust separated in the filter (valuable product) is conveyed pneumatically to the filter of the main dedusting system (3.27), from where it is fed back into the process chain.

Sorting

- Magnetic separation

The pre-shredded and dried battery cells, unit sizes approx. <60mm, are fed directly from the dryer onto a conveyor belt, 500mm wide. The conveyor belt (3.12) passes through an overbelt magnetic

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

separator (3.13) to separate magnetizable metal components in a first step. The resulting Fe product is ejected into suitable pallets. An overband magnetic separator, manufactured by Steinert, with a working width of 650 mm was selected as the separator. The magnetically separated material is fed directly from the conveyor belt into a cross-flow separator (3.14).

- Separation of heavy parts

This second sorting step is intended for the rough separation of heavy parts (housing parts, bridges, nuts, bolts and the like). The light fraction largely consists of foils (copper, aluminum, plastic) and the active mass to be recovered as powder. So-called cross-flow separators are a simple unit for such a separation process. The material to be sorted is scattered into an almost horizontal air stream and deflected to varying degrees depending on the mass of the individual material components. While heavier parts are collected in a first chamber, the air flow transports lighter parts to a second chamber. Dust is discharged from the separator with the air flow and collected separately in cyclone or filter separators. The equipment available on the market appears to be oversized for the quantities of material to be processed. It is therefore recommended to build a machine of a suitable size and shape as a custom-made product.

- Digestion comminution

The light fraction from the cross-flow classifier can contain large aggregates of active mass in addition to considerable proportions of incompletely broken down composites of arrester films and active mass. In order to achieve the desired high yield of the active mass, the light classifier material produced must be subjected to a further pulping process. A MEWA UG600 granulator (3.16) was selected for this disintegration comminution. The degree of digestion can be adjusted with this machine by selecting a suitable sieve grate. The disintegration shredding process should remove the active mass as completely as possible from the metal foils without shredding these foils too finely.

- Screen classification

Due to the large differences in the particle sizes of the components to be separated, sieving at e.g. 1 mm sieve mesh width is suitable for separating the active mass from the granulator's comminution product. Experience has shown that with this screen mesh size, the pulverized active mass can be separated very reliably from the films. For screening, the granulator product is fed to the screening machine together with the dust separated in the dedusting systems. An MHR 7/20/III multi-deck horizontal screening machine from Siebtechnik (3.18) was selected for this sorting task.

The sieve underflow, active mass in powder form, is fed by means of a suitable screw conveyor (3.19) to a drum filler with palletizing device (3.20) and packaged. The screen overflow, a mixture of copper and aluminum foil sections contaminated with plastic, is also fed onto an air oven (3.22), also known as a separating table, by means of a screw conveyor (3.21).

Further processing of the film fraction

In order to be able to market the metal foils at a higher profit, it is necessary to separate them to a large extent. Due to the widely varying specific weights of the metals contained, density sorting processes are suitable for separation. In dry processing, so-called air baffles have been introduced as effective sorters. A TTS 300/1000/1 separating table from TRENNSO Trenntechnik was selected for this sorting task.

The air hearth consists of an inclined, horizontally oscillating porous plate through which air flows. Under appropriate conditions, most of the separation tables introduced allow the separation of mixtures of particles of different weights into two products. Specifically heavier particles move to the upper end of the inflow bottom, whereas the lighter particles float to the lower discharge end. With these hearth designs with two-product separation, only one product with a higher purity can ever be

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

achieved. This is accompanied by losses and a deterioration in the quality of the other product.

The metal foils (foil thickness approx. 20 µm) have bulk weights of between 150 kg/t and 300 kg/t in the as-collected state and could therefore neither be transported effectively nor used in melting operations. To do this, they must be pressed into briquettes of the appropriate density. Suitable briquetting presses are available on the market for this purpose.

A RUF 5.5/1700/80 (3.26) was selected as the briquetting press. The throughput capacity of the briquetting presses is primarily dependent on the bulk weight of the press feed material. As the properties of the film fractions produced in the future are currently unknown, the selection of the press size is based solely on the nominal throughput capacity according to the manufacturer.

In order to be able to process the film fractions separately on a press, two buffer containers (3.24) must be installed between the separating table and the briquetting press, which can hold at least one day's production, approx. 2.5 m^3 , of the corresponding film fraction. This keeps product changes at the briquetting press to a minimum, which helps to reduce the quantity of mixed briquettes.

Extraction and dedusting system

The following number and type of extraction points are assumed for estimating the air volumes required for dedusting the system:

Table G-4: Estimate of the required dedusting air volumes

Suction point	Quantity	Required air volume [m3/min]	Required total air volume [m^3/h]
Product transfer points	8	30	14,400
Container	2	20	2,400
Granulator	1	60	3,600
Overbelt magnetic separator	1	30	2,160
Air stove	1	0.5	30
Cross-flow classifier	1	40	2,400
Pneumatic transport	1	0.5	30
Total			**25,020**

The estimated total air volume required is around 25,000 m^3/h. Assuming that 15% of the active mass contained in the feed quantity used, approx. 300 kg, is released in the form of dust during processing and must be captured, a loading of the dedusting air of 1.8 gFS/m^3 can be estimated.

If it is assumed that all volatile, highly flammable solvents have been removed during the drying process, no explosion protection is required for the dedusting of the sorting plant from the dryer discharge. Dust from the pre-shredding/drying process is fed into the main dust extraction system at the same time (pneumatic conveying). This means that all dust is collected centrally and fed into the drum filling process.

The process flow diagram for the entire mechanical processing of the battery cells, which is shown in Figure G-1, provides another overview of the individual components of the system and the material flows within the system.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

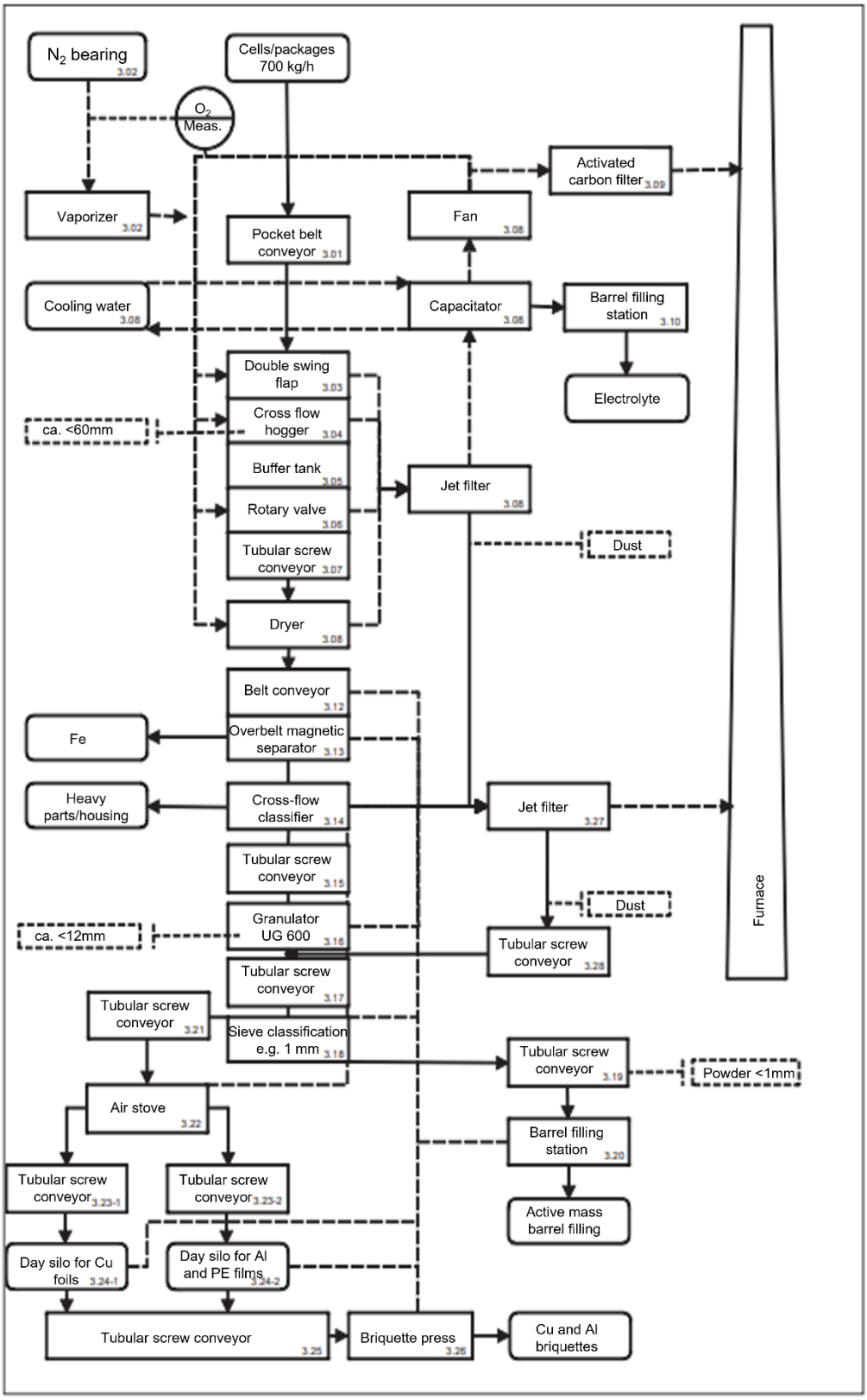


Figure G-1: Mechanical treatment process flow chart

G.3 Planning the overall system and designing the process steps

Based on the laboratory tests for the upstream steps of the recycling process, the requirements for the input materials for Chemetall's recycling process were determined. The procedure for planning the overall system was agreed at a kick-off meeting in Brunswick.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

The capacity of the pilot plant for the mechanical separation of battery materials was specified. Furthermore, a specification of the contamination limits of the products of the pilot plant was submitted.

The individual process steps of mechanical processing were evaluated in order to determine the optimum process chain for the subsequent hydrometallurgical process. It is important to ensure the highest ecological and economic efficiency in the recovery of lithium and transition metal salts.

Planning principles

The following framework conditions were defined for the design of the system.

- Processing capacity of 700 kg cell mass per hour
- Single-shift operation
- The battery types to be processed are lithium-ion batteries in the form of traction batteries, hybrid batteries and plug-in batteries
- No thermal treatment of the accumulator cells is planned

Arrangement and interlinking of the storage, dismantling and mechanical processing areas

The interlinking and specific design of the individual work areas within the overall system have already been discussed at the relevant points in **AS G.1** and **AS G.2**. It should be briefly summarized here that the transport from the receiving warehouse to the dismantling stations is performed by forklift truck and the discharged battery cells are transported onwards for mechanical processing using pocket belt conveyors. Transport within the mechanical processing system is pneumatic. As can be seen in Figure G-2, this internal transport is necessary because the entire plant is divided into three areas.

Deliveries are made to the incoming goods warehouse, where pre-unloading also takes place. The battery systems delivered by truck are removed by forklift truck and stored. The forklift truck then also takes the corresponding battery systems to the dismantling station.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

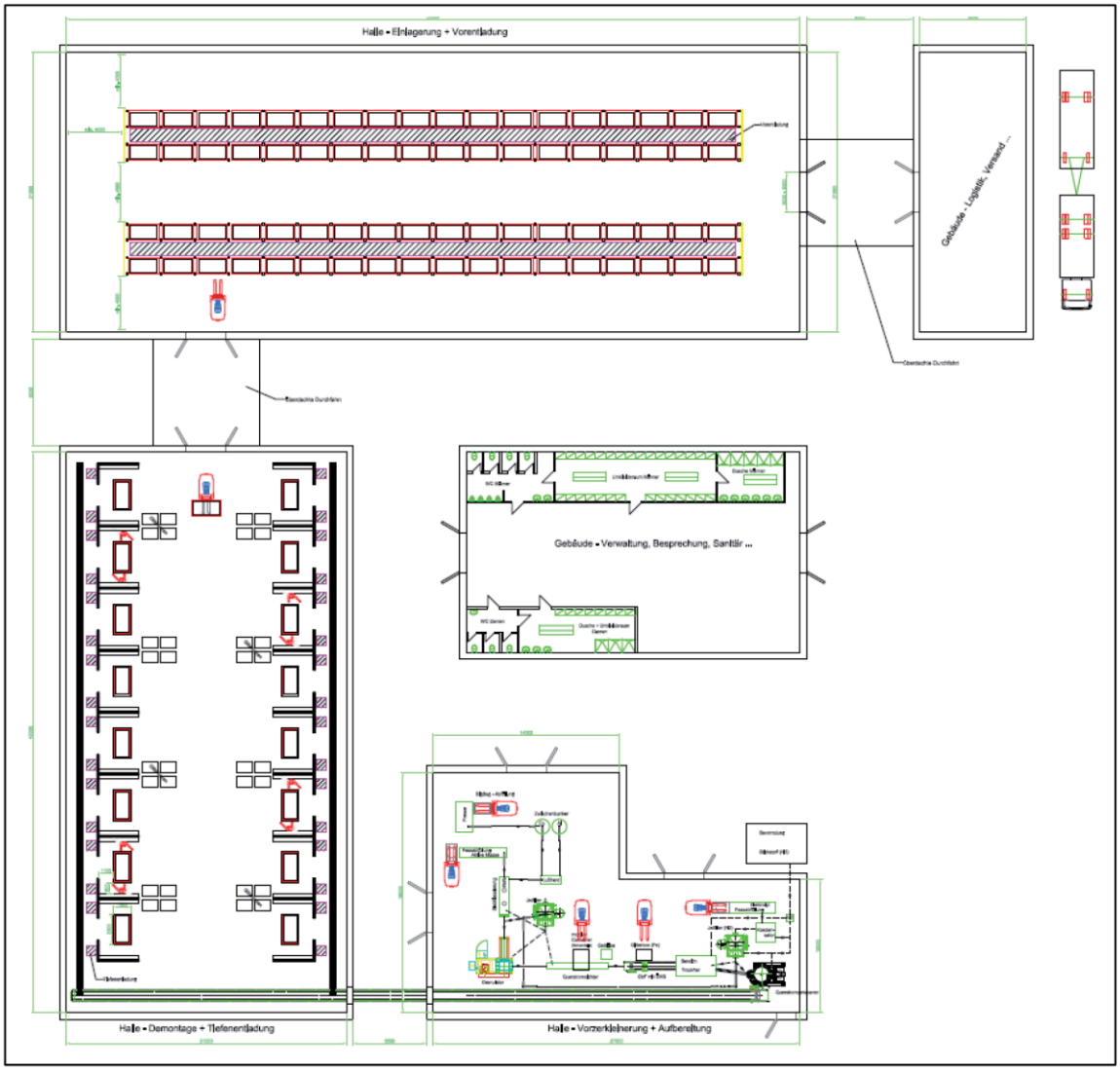


Figure G-2: Layout of the processing plant for lithium-ion batteries

Once the battery systems have been dismantled and the cells removed, they are placed on a pocket belt conveyor and transported to the mechanical processing area. Within this processing plant, transportation after shredding, the first process step, is exclusively pneumatic.

Material flow planning

The material flow is divided into two areas: dismantling and mechanical processing (see Figure G-3). During dismantling, the system and module housings, which are usually made of steel or aluminum, as well as copper-containing busbars and cables, are removed. The plastic content also comes mainly from the housing, as well as from the cooling system.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

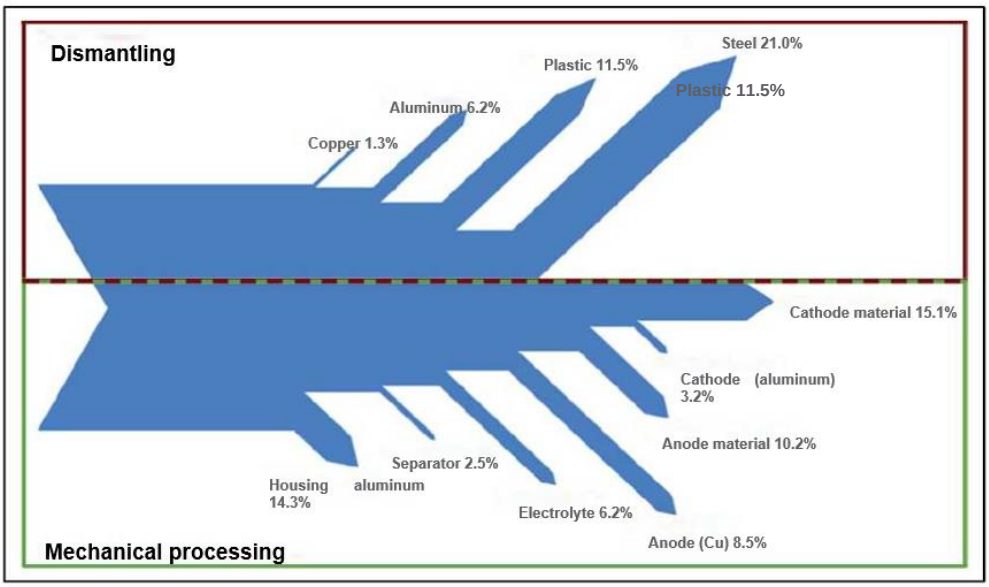


Figure G-3: Sankey diagram of the material flow in the processes

The substances from the mechanical processing all come from the battery cells. The aluminum of the cathode is the current collector foil to which the active material is applied. The graphite of the anode is applied to a copper current collector foil. The cathode material is further processed in later steps in the Chemetall plant.

Acceptance, storage of traction batteries and product fractions, shipping

The batteries are transported to the dismantling plant on trucks with support. Traction batteries are low-voltage power supply systems within the meaning of DIN VDE 0100-717 and must therefore be processed as such.

For this reason, batteries should not be handled and stored in an open-air warehouse, but in closed rooms. The warehouse is designed to hold input material for a period of ten working days.

The batteries are unloaded from the delivery vehicle on the transport racks and received in the warehouse described below.

Assuming that only batteries without leaks (TÜV) may be used for vehicles on public roads, repackaging is not necessary (mass and space saving). Batteries destroyed in traffic accidents or other incidents do not account for the majority of used batteries and are therefore not the subject of further consideration.

The batteries are accepted through a material lock measuring approx. 2.50 m wide x 2.50 m high. If two production weeks (ten working days) are kept in stock, a calculated storage capacity for 431 large traction batteries must be created.

Assuming dimensions of 2.0 m x 1.0 m x 0.5 m, storage for several days in heavy-duty racks is recommended. The basic discharge of the accumulators is performed in the storage area to utilize the built-up area. These racks are operated by forklift trucks or stacker cranes, which stack them and, after basic unloading, transport them directly to the dismantling stations or transfer them to flat transport vehicles.

The processing plant should have a capacity to process a cell mass of 700 kg/h. The processing plant is operated in a single shift.

Table G-5: Calculation of the storage requirements for the battery types

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

	Traction, large	Traction, small	Hybrid
Battery dimensions	1 m x 2 m	1 m x 0.6 m	0.8 m x 0.5 m
Cell mass/unit.	130 kg	75 kg	25 kg
Quantity	431	747	2240
Total mass/unit.	300 kg		
Total mass	129 t		
Special storage requirements	0,35 t/m^2	0,8 t/m^2	0,8 t/m^2
Net storage requirements	370 m^2		

For further considerations, the storage of large traction batteries in six units on top of each other is assumed. This means that 370 m^2 of storage space is required to store 432 batteries plus the necessary space for shelving. Taking into account the necessary logistics areas (operation of the storage racks), a floor area of 1,155 m^2 should be provided for the warehouse. Assuming an eaves height of 6 m and a ridge height of 8 m, a building design with a flat pitched roof results in a built-up area of 8,100 m^3 and a ridge height of 8 m.

The warehouse itself remains a cold room and is constructed from uninsulated Lindapter wall elements. For operation, the room is equipped with lighting that is sufficiently dimensioned for handling and storage work.

As no batteries are to be opened in the storage area, there is no need for ventilation.

The products produced, with the exception of coarse metal fractions (battery housings, non-ferrous metals), which can be stored outdoors, are temporarily stored in the logistics and shipping building to be erected for this purpose.

Appropriate containers must be set up outside for the storage of coarse metal fractions.

The products resulting from the processing of the accumulator cells result in an estimated storage space requirement, which can be seen in Table G-6 below.

Table G-6: Estimate of storage space requirements for the products

Material	kg/h	Barrel/h	Pallets /d
Electrolyte liquid	74	0.37	1.48
Active mass	300	1.25	5
Aluminum briquettes	44		0.3 BigBag
Copper briquettes	122		0.35 BigBag

Equipment of the entire system

Table G-7 provides an overview of the individual items listed in the process flow diagram and which are reflected in the layout of the overall system. In addition to the item designation and the required number of items, this table also contains technical data, if available, as well as possible manufacturers of the devices.

Table G-7: List of machinery and equipment

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

No.	Designation	Type/technical data	Manufacturer	Quantity
1.0	***Storage and transportation technology***			
1.01	Storage rack	LxWxH: 45.0x4.5x5.0 m (2 units)	GALLER Storage and shelving technology	2
1.02	Narrow-aisle forklift		Köttgen Service GmbH Kerpen	3
1.03	Discharge fittings			4
2.0	***Unloading and dismantling***			
2.01	Dismantling stations			16
2.02	Lifting gear			16
2.03	Tool equipment			16
2.04	Unloading cutlery			16
3.0	***Mechanical processing***			
3.01	Pocket belt conveyor			1
3.02	Nitrogen supply	12000 l. Tank system, incl. evaporator	Linde rental plant	1
3.03	Entry sluice	e.g. double swing flap or double slider with pressure relief		1
3.04	Cross-flow hogger	QZ 1200 depressurized	MEWA	1
3.05	Buffer tank	100 liter capacity;		1
3.06	Discharge sluice	Rotary valve diam. 400mm; pressure-resistant		1
3.07	Tubular screw conveyor	200mm x 2m		1
3.08	Drying system	2000 m^3/h; incl. pulse jet filter; blower, condenser explosion-proof incl. pressure relief devices		1
3.09	Activated carbon filter		NORIT rental system	
3.10	Condensate filling	SlimLine 6.1-00 explosion-proof with drum palletizing	Feige Filling GmbH	1
3.11	Pipeline - pre-shredding + drying	Stainless steel version		1
3.12	Conveyor belt to the magnetic separator	500mm x 6m partial stainless steel		1
3.13	Overband magnetic separator	Steinert UM 650mm	Steinert electromagnet construction	1
3.14	Cross-flow classifier		Self-build	1
3.15	Tubular screw conveyor	140mm x 5m		1
3.16	Granulator	UG600	MEWA	1
3.17	Tubular screw conveyor	140mm x 3m		1
3.18	Screening machine	Horizontal multi-deck screening machine MHR 7/20/III	Screening technology Mülheim	1
3.19	Tubular screw conveyor	80mm x 3 m for screen underflow		1
3.20	Barrel filling	Drum filling station with drum palletizing	Hecht technology	1
3.21	Tubular screw conveyor	140mm 3m sieve overflow to the air heater		1
3.22	Air stove	TTS 300/1000/1 (incl. container and dosing unit)	Trennso separation technology	1
3.23	Screw conveyors for hearth products	140mm x 6m		2
3.24	Daily silo for stove products			2
3.25	Screw conveyors to the briquette press	140mm x 8m		1
3.26	Briquette press	RUF 5.5/1700/80	RUF	1
3.27	Pulse jet filter for system dedusting	25000 m^3/h, incl. blower, piping, extraction hoods		1

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

No.	Designation	Type/technical data	Manufacturer	Quantity
3.28	Tubular screw conveyor	80mm x 2m for dust extraction		1

H Bibliography

Bass, F. M. (1969): A New Product Growth for Model Consumer Durables. Management Science, Vol. 15, No. 5, pp. 215-227.

Buchert, M; Jenseit, W.; Merz, C.; Schüler, D. (2011): Life cycle assessment of the “Recycling of lithium-ion batteries” (LithoRec). Final report. Öko-Institut e. V., Darmstadt

Hoyer, C.; Kieckhäfer, K.; Spengler, T. (2011): Strategische Planung des Recyclings von Lithium-Ionen-Traktionsbatterien, in: SUCKY, E.; ASDECKER, B.; DOBHAN, A.; HAAS, S.; WIESE, J. (eds.): Logistikmanagement: Herausforderungen, Chancen und Lösungen, Band II, Tagungsband der Logistikmanagement 2011, University of Bamberg Press, Bamberg, pp.399-419.

Konietzko, S.; Gernuks, M. (2011): Resource availability of secondary raw materials. Potential analysis for lithium and cobalt. Umbrella working group on resource availability as part of the BMU-funded LithoRec and LiBRi projects. Final report. O.V.

Sarre, Guy; Blanchard, Philippe; Broussely, Michel (2004): Aging of lithium-ion batteries. Journal of Power Sources 127 (2004), pp. 65 - 71.

Federal Statistical Office (2009): Statistics on the number of motor vehicles and trailers. Status: 07/19/2010. Retrieved on: 07/19/2010. http://www-genesis.destatis.de.

Sterman, J. D. (2000): Business Dynamics: Systems Thinking and Modeling for a Complex World. Boston: Irwin McGraw-Hill

UN (2008): European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) - Applicable as from 1 January 2009. Edited by: United Nations Publications. ISBN 978-92-1-139131-2.

http://www.unece.org/trans/danger/publi/adr/adr2009/09ContentsE.html.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

I Annexes

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 1: Exogenous factors of waste battery generation

Identifier	Description	Variable reference	Unit of measurement
A1	Initial market potential	Drive concept	1,000 vehicles
A2	Time of achievement (for A1)		Year
A3	Long-term market potential		1,000 vehicles
A4	Time of achievement (for A3)		Year
A5	Expected service life of the vehicle		Year
B1	Average cell capacity of the Reference battery		kWh
B2	Average cell capacity of the Reference battery		Ah
B3	Mass of the reference battery		kg
B4	Capacity of the reference battery		kWh
C1	Expected share of battery variant in drive concept	Drive concept and battery variant	Percent
C2	Average number of cells in the battery system per battery variant and drive concept		Cell
C3	Expected service life for operation as a traction battery		months
D1	Average delay in response	Further use outside the system	months
D2	Proportion of delayed returns		Percent

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 2: Scenario parameterization, mass (B3) and capacity (B4) of the batteries

		HEV[29]	PHEV[30]	BEV[31]
Battery mass (B3)	[kg]	38	140	255
Battery capacity (B4)	[kWh]	1.3	12.1	23.0

[29] Reference: Audi Q5 hybrid battery.

[30] Mass and capacity from umbrella LCA boundary conditions.

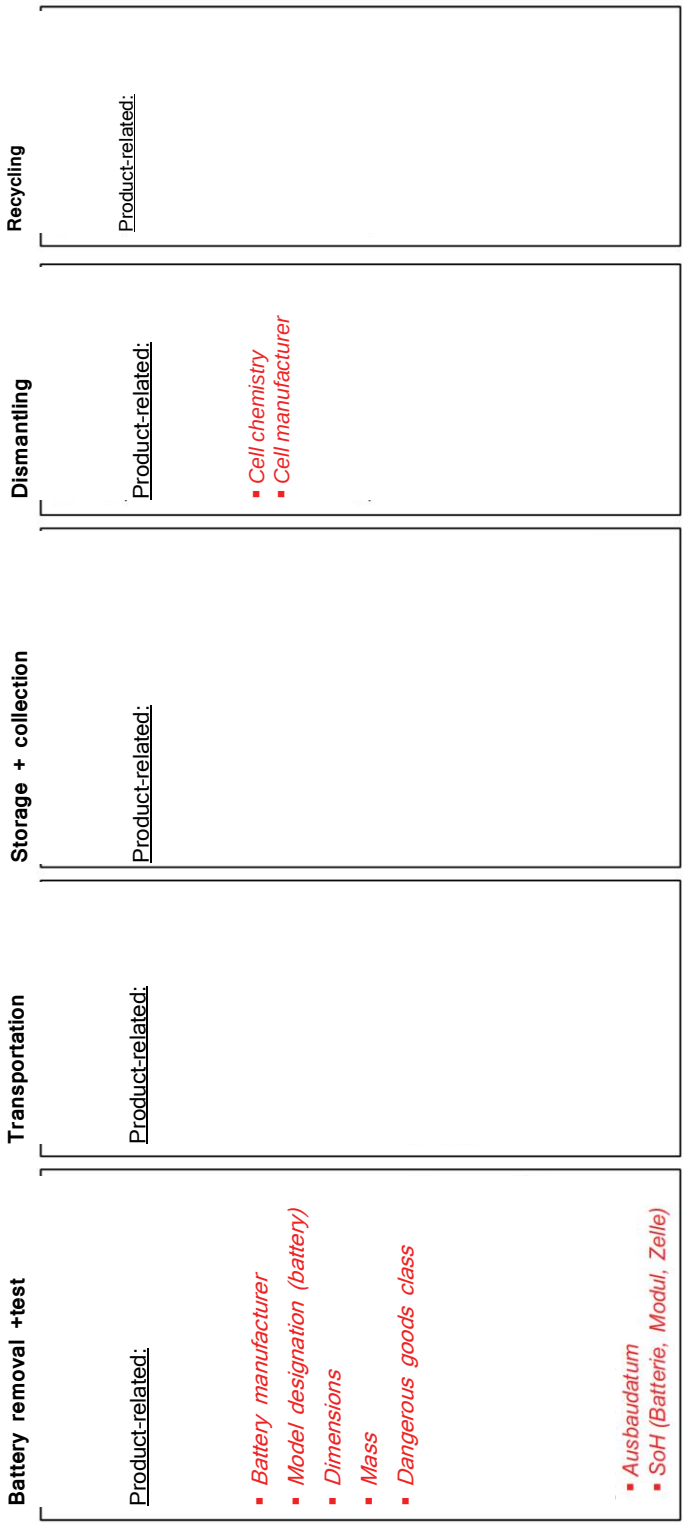
[31] Based on a 23 kWh battery and an energy density of 90 Wh/kg (umbrella LCA boundary conditions). Reference: VW E-Up! Energy density from umbrella LCA boundary conditions. Mass determined by calculation.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 3: Information requirements along the process chain

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 4: Information offered along the process chain



This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 5: Battery types, normalization, capacity and transformation coefficient

Battery type	**Standardization** [BEV equivalents]	**Capacity coefficient transshipment warehouse and dismantling plant** [cap. units/BEV eq.]	**Transformation coefficient cells** [kg/BEV-eq.]
HEV	0.1	0.1	20
PHEV	0.5	0.5	100
BEV	1.0	1.0	200
BEV-eq.	1.0	1.0	200

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 6: Transportation costs for battery systems (pre-/main run) and cells

	Pre-run (collection) **Sources for transshipment warehouses and dismantling plants**	Main run **Transhipment warehouse to dismantling plants**	Cell transport **[EUR/(t*km)]**
Acceptance	No stacking, 4 Euro pallets per BEV equivalent, vans)	Collective transport, no stacking, 4 Euro pallets per BEV equivalent, 40-tonner	Collective transport, max. 25 tonnes payload, 40-tonne truck
Cost rate per 100 km	60 EUR/100 km	140 EUR/100 km	140 EUR/100 km
Aver. Transport quantity	1 BEV-eq.	8.25 BEV-eq.	25 t cells
Specific transportation cost rate	0.600 EUR/(BEV-eq.*km)	0.170 EUR/(BEV-eq.*km)	0.056 EUR/(t*km)

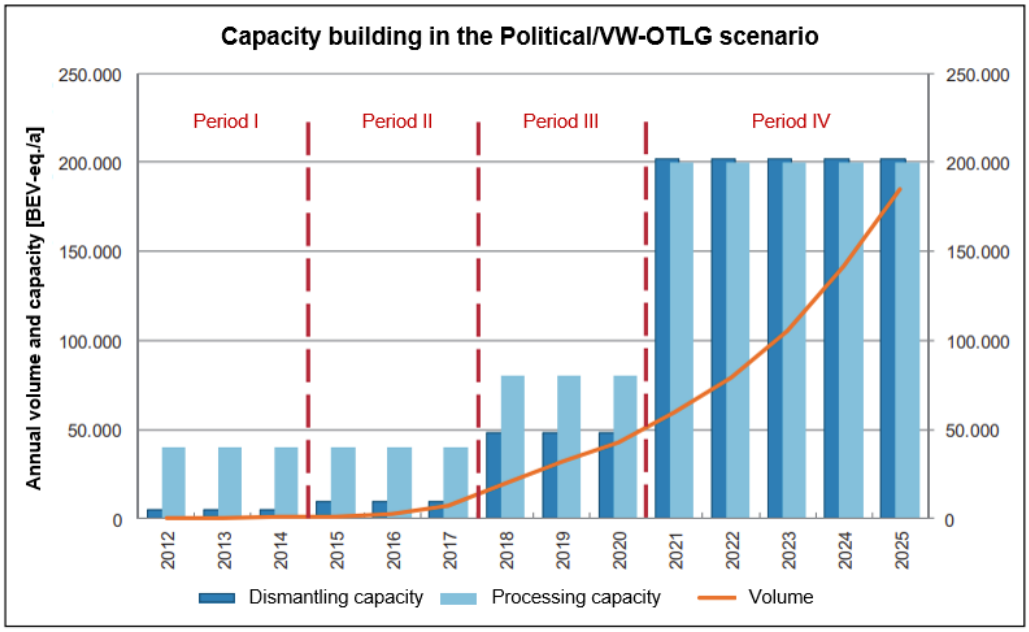
This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 7: Capacity classes and payments for transshipment warehouses, dismantling and processing plants

Module	Transshipment warehouse		Dismantling plant		Processing plant
Class	Small	Large	Small	Large	Large
Capacity	10,000 BEV eq./a	100,000 BEV-eq/a	4.800 BEV-eq./a	38.400 BEV-eq./a	8,000 t cells/a
Establishment payment	327,900 EUR	1,487,000 EUR	558,000 EUR	1,710,000 EUR	14,602,000 EUR
Fixed annual payments	47,000 EUR/a	87,000 EUR/a	273,000 EUR/a	930,000 EUR/a	1,612,000 EUR
Equalized contribution margin	-3.50 EUR/BEV-eq.		(75 EUR/BEV-eq.)		(1.196 EUR/kg)

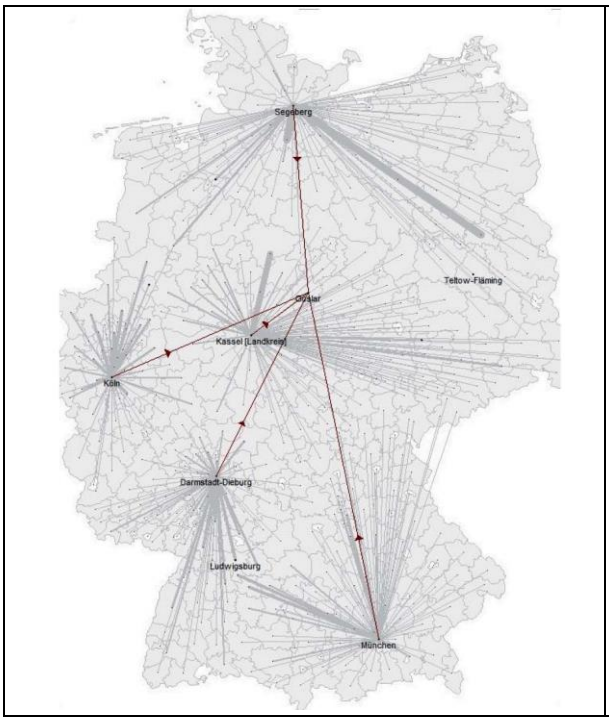
This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 8: Capacity expansion for dismantling and reprocessing in relation to the volume of spent batteries in the planning period

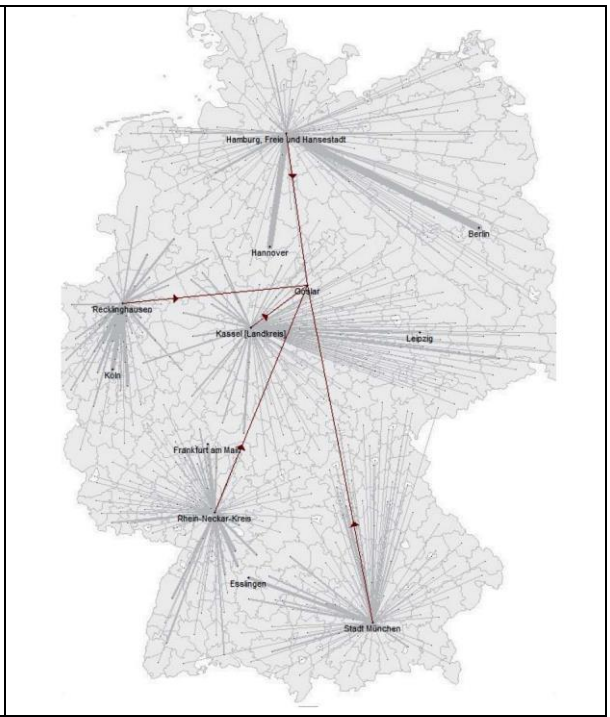


This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 9: Comparison of the network structures when specifying VW-OTLG (a) and VG-10 (b) site quantities when realizing the "Realistic" scenario in the fourth period



a) Network structure "Realistic/VW-OTLG", period IV



b) Network structure "Realistic/VG10", period IV

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 10: Handling capacity and total investment estimate for small and large transshipment warehouses

Reference	Posts	Unit	Small	Large
Handling and storage capacity	**Handling capacity max.**	**BEV-eq./a**	**10,000**	**100,000**
	Handling capacity at 50 handling operations per year		2,500	25,000
	Handling capacity at 100 handling operations/a		5,000	50,000
	Storage capacity	**BEV-eq.**	**50**	**500**
Storage technology	Shelf type	Type	1	2
	Number of shelves required	Shelves	5	32
	Specific investment in storage technology	**EUR**	**8,500**	**54,400**
Building	Storage and conveyor floor area	sqm	188	1204
	Storage and conveyor floor area with surcharge	sqm	207	1324
	Hall floor area, total	sqm	300	1400
	Specific investment in buildings	**EUR**	**240,000**	**1,260,000**
Property	Side dimension for square hall	m	17	37
	Development area, rounded	sqm	180	380
	Plot area	sqm	480	1780
	Specific investment Land	**EUR**	**14,400**	**53,400**
Conveyor technology	Number of industrial trucks required	Vehicles	1	2
	Specific investment in conveyor technology	**EUR**	**30,000**	**60,000**
Security container	Number of F90 safety containers required	Container	1	2
	Specific investment Security container	**EUR**	**35,000**	**70,000**
	Total investment	**EUR**	**327,900**	**1,497,800**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 11: Estimate of investment-related costs for small and large transshipment warehouses

Reference	Posts		Small [EUR]	Large [EUR]
Calc Interest rate		9%		
Calc Interest costs		Residual value*		
	Property	100%	1,296	4,806
	Building	0%	10,800	56,700
	Storage technology	10%	459	2,938
	Conveyor technology	5%	1,485	2,970
	Security container	10%	1,890	3,780
	Imputed interest costs		**15,930**	**71,194**
Calc Depreciation costs[32]		Useful life [a]		
	Building	40	6,000	31,500
	Storage technology	20	383	2,448
	Conveyor technology	20	1,425	2,850
	Security container	20	1,575	3,150
	Imputed depreciation costs		**11,715**	**39,948**
Repair and maintenance costs		Cost rate*		
	Land and buildings	0.80%	2,035	10,507
	Storage technology	1.00%	85	544
	Conveyor technology	2.00%	600	1,200
	Security container	1.00%	350	700
	Repair and maintenance costs		**3,070**	**12,951**
Other capital expenditures h. Costs	Investment-related management	0.50%	1,640	7,489
	Investment-related insurance	1.00%	3,279	14,978
	Imputed risk	0%	□	□
	Other investment-related costs		**4,919**	**22,467**
Total investment-related costs			**33,301**	**146,560**

*) As a proportion of the specific investment

[32] Land is not subject to wear and tear and is not depreciated.

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 12: Imputed and pagatoric annual fixed costs of transshipment warehouses

Reference	Posts	Small [EUR]	Large [EUR]
Imputed Costs	**Imputed costs incl. FfU**	**25,313**	**111,142**
Pagatoric costs	attributable investment-related costs	7,989	35,418
	Incidental operating costs	3,600	16,800
	Management personnel costs (BPK surcharge)	15,750	63,000
	Other overheads (BPK mark-up)	15,750	63,000
	Pagatoric costs	**43,089**	**178,218**
	Fixed costs	**68,401**	**289,360**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 13: Estimate of the total investment for the construction of small and large dismantling plants

Reference	Posts	Unit	Small	Large
Dismantling service	Daily dismantling capacity	BEV-eq/d	20	200
	Daily dismantling capacity	t BEV- eq/d	7	66
	Annual maximum dismantling capacity	BEV-eq/a	6,000	60,000
	Annual maximum dismantling capacity	t BEV- eq/a	1,980	19,800
Storage and conveyor technology	Storage requirements systems	BEV-eq.	25	250
	Storage technology systems	EUR	3,400	27,700
	Storage technology parts	EUR	3,000	20,000
	Conveyor technology systems	EUR	4,000	20,000
	Number of F90 safety containers required	Unit	1	2
	F90 safety container	EUR	35,000	70,000
	Number of industrial trucks required	Unit	2	4
	Investment in industrial trucks	EUR	60,000	120,000
	Special investment in storage and conveyor technology	**EUR**	**104,800**	**265,400**
System test and discharge stations	Number of test stations	Unit	1	2
	Number of unloading stations	Unit	3	29
	Space requirement	sqm	16	147
	Special investment Test and unloading stations	**EUR**	**47,000**	**416,000**
Dismantling stations	Number of dismantling stations	Unit	2	11
	Space requirement	sqm	60	330
	Specific investment Dismantling stations	**EUR**	**6,000**	**33,000**
Cell unloading stations	Number of unloading stations	Unit	3	29
	Space requirement	sqm	9	87
	Specific investment Cell discharging stations	**EUR**	**63,000**	**609,000**
Building & property	Warehouse size	sqm	150	1,000
	Investment in warehouse	EUR	120,000	800,000
	Size of dismantling plant	sqm	200	800
	Investment in dismantling plant	EUR	160,000	640,000
	Plot size	sqm	525	2,700
	Investment property	EUR	15,750	81,000
	Special investment buildings & land	**EUR**	**296,625**	**1,525,500**
	Sum of specific investments	**EUR**	**517,425**	**2,848,900**
	Factor for contingencies (FfU)	8%	41,394	227,912
	Total investment	**EUR**	**558,819**	**3,076,812**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 14: Estimate of investment-related costs for small and large dismantling plants

Reference	Posts		Small [EUR]	Large [EUR]
	Calc Interest rate	9%		
Calc Interest costs		Residual value*		
	Storage technology	10%	346	2,576
	Conveyor technology	5%	3,168	6,930
	Security container	10%	1,890	3,780
	Test and unloading stations Systems	10%	2,538	22,464
	Dismantling stations	5%	297	1,634
	Cell discharging stations	10%	3,402	32,886
	Building	0%	12,600	64,800
	Property	100%	2,126	10,935
	Imputed interest costs		**26,367**	**146,004**
Calc Depreciation costs		Useful life [a]		
	Storage technology	20	288	2,147
	Conveyor technology	20	3,040	6,650
	Security container	20	1,575	3,150
	Test and unloading stations Systems	20	2,115	18,720
	Dismantling stations	20	285	1,568
	Cell discharging stations	20	2,835	27,405
	Building	40	7,000	36,000
	Imputed depreciation costs		**17,138**	**95,639**
Repair and maintenance costs		Cost rate*		
	Storage technology	1.00%	64	477
	Conveyor technology	2.00%	1,280	2,800
	Security container	1.00%	350	700
	Test and unloading stations Systems	1.00%	470	4,160
	Dismantling stations	1.00%	60	330
	Cell discharging stations	1.00%	630	6,090
	Land and buildings	0.80%	2,366	12,168
	Repair and maintenance costs		**5,220**	**26,725**
Other capital expenditures h. Costs	Investment-related management	0.50%	2,587	14,245
	Investment-related insurance	1.00%	5,174	28,489
	Imputed risk	0%	-	-
	Other investment-related costs		**7,761**	**42,734**
Total investment-related costs			**56,486**	**311,102**
	Factor for contingencies (FfU)	8%	4,519	24,888
Total investment-related costs			**61,005**	**335,990**

*) As a proportion of the specific investment

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 15: Imputed and pagatoric annual fixed costs of the dismantling plants

Reference	Posts	Small [EUR]	Large [EUR]
Imputed costs	**Imputed costs incl. FfU**	**46,985**	**260,975**
Pagatoric costs	attributable investment-related costs incl. FfU	14,020	75,015
	Incidental operating costs	4,200	21,600
	Management personnel costs (BPK surcharge)	104,250	460,500
	Other overheads (BPK mark-up)	104,250	460,500
	Pagatoric costs	**226,720**	**1,017,615**
	Fixed costs	**273,705**	**1,278,590**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 16: Investment estimate for small and large mechanical processing plants

Reference	Posts	Surcharge rate (rounded) [%]	Special investment	
			Small [EUR]	Large [EUR]
Direct investments	Basic investment		**860,000**	**2,150,000**
	Piping (installed)	10%	84,417	211,043
	Electrics (installed)	6%	52,761	131,902
	Buildings (including service)	15%	131,902	329,755
	Site development	9%	79,141	197,853
	Operating equipment and ancillary facilities	25%	211,043	527,607
	Direct investments		**1,419,264**	**3,548,160**
Indirect investments	Technical planning and construction supervision	20%	174,110	435,276
	Site management	24%	205,767	514,417
	Approval procedure	2%	21,104	52,761
	Fees for contractors	10%	89,693	224,233
	Unforeseen events	21%	184,663	461,656
	Indirect investments		**675,337**	**1,688,344**
	Fixed asset investment	**244%**	**2,094,601**	**5,236,503**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 17: Estimate of investment-related costs for small and large mech. Processing plants

Reference	Posts		Small [EUR]	Large [EUR]
Calc Interest rate		9%		
Calc Interest costs		Residual value*		
	Apparatus and machines	5%	42,570	106,425
	Pipelines	5%	4,179	10,447
	Electrics	5%	2,612	6,529
	Building	0%	5,936	14,839
	Property	100%	10,684	26,710
	Operating equipment & ancillary facilities	5%	10,447	26,117
	Indirect investments	0%	30,390	75,975
	Imputed interest costs		**106,817**	**267,042**
Calc Depreciation costs		Useful life [a]		
	Apparatus and machines	20	40,850	102,125
	Pipelines	20	4,010	10,025
	Electrics	20	2,506	6,265
	Building	40	3,298	8,244
	Operating equipment & ancillary facilities	20	10,025	25,061
	Indirect investments	20	33,767	84,417
	Imputed depreciation costs		**94,455**	**236,137**
Repair and maintenance costs		Cost rate*		
	Land and buildings	0.80%	1,688	4,221
	Apparatus and machines	2.00%	17,200	43,000
	Pipelines	1.50%	1,266	3,166
	Electrics	1.00%	528	1,319
	Operating equipment & ancillary facilities	1.00%	2,110	5,276
	Repair and maintenance costs		**22,793**	**56,982**
Other capital expenditures h. Costs	Investment-related management	0.50%	10,473	26,183
	Investment-related insurance	1.00%	20,946	52,365
	Imputed risk	0%	-	-
	Other investment-related costs		**31,419**	**78,548**
Total investment-related costs			**255,483**	**638,708**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.

Annex 18: Imputed and pagatoric annual fixed costs of the mechanical processing plants

Reference	Posts	Small [EUR]	Large [EUR]
Imputed costs	**Imputed costs**	**201,272**	**503,179**
Pagatoric Costs	attributable investment-related costs	54,212	135,529
	Incidental operating costs	2,400	14,400
	Management personnel costs (BPK surcharge)	31,500	52,500
	Other overheads (BPK mark-up)	31,500	52,500
	Pagatoric costs	**119,612**	**254,929**
	Fixed costs	**320,883**	**758,108**

This work is protected by copyright and may not be reproduced in any form or passed on to third parties.
It is for personal use only.