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Evaluation of a Remanufacturing for Lithium Ion Batteries from Electric Cars

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Abstract**—**Electric cars with their fast innovation cycles and their disruptive character offer a high degree of freedom regarding innovative design for remanufacturing. Remanufacturing increases not only the resource but also the economic efficiency by a prolonged product life time. The reduced power train wear of electric cars combined with high manufacturing costs for batteries allow new business models and even second life applications. Modular and intermountable designed battery packs enable the replacement of defective or outdated battery cells, allow additional cost savings and a prolongation of life time. This paper discusses opportunities for future remanufacturing value chains of electric cars and their battery components and how to address their potentials with elaborate designs. Based on a brief overview of implemented remanufacturing structures in different industries, opportunities of transferability are evaluated. In addition to an analysis of current and upcoming challenges, promising perspectives for a sustainable electric car circular economy enabled by design for remanufacturing are deduced. Two mathematical models describe the feasibility of pursuing a circular economy of lithium ion batteries and evaluate remanufacturing in terms of sustainability and economic efficiency. Taking into consideration not only labor and material cost but also capital costs for equipment and factory facilities to support the remanufacturing process, cost benefit analysis prognosticate that a remanufacturing battery can be produced more cost-efficiently. The ecological benefits were calculated on a broad database from different research projects which focus on the recycling, the second use and the assembly of lithium ion batteries. The results of this calculations show a significant improvement by remanufacturing in all relevant factors especially in the consumption of resources and greenhouse warming potential. Exemplarily suitable design guidelines for future remanufacturing lithium ion batteries, which consider modularity, interfaces and disassembly, are used to illustrate the findings. For one guideline, potential cost improvements were calculated and upcoming challenges are pointed out.

Keywords**—**Circular economy, electric mobility, lithium ion batteries, remanufacturing.

I. INTRODUCTION

IN the past years, electric vehicles (EVs) have been generating interest from the automobile, technology industry and the public alike [1]. The growing market will lead to the emergence of end-of-first-life batteries and has initiated the debate for the best strategies for this secondary market [2]. Due to the degenerative nature of lithium-ion batteries (LIB), an end-of-first-life battery is deemed unsuitable to meet EV standards when the available capacity reaches 80% [3]. However, it may still hold the capacity to carry sufficient charge for use in further applications [4]. All processes that take advantage of the residual value of end-of-life batteries are summarized in a collective term, called post-first-life applications. Second use, remanufacturing and recycling all fall within this umbrella term. Essentially, post-first life applications are activities that carry out the approach of a circular economy to minimize waste, reduce system risks and optimize resource yields [5]. An efficient circular economy can help to improve the cost structures of LIBs and electric cars respectively. However, diverse challenges have to be solved to ideally combine all post-first-life possibilities. In particular, the design phase of the batteries is already crucial for their subsequent suitability in post-first-life applications [6]. Furthermore, the processes for the disassembly and remanufacturing define the cost structures significantly and need to be optimized for a universal process [7]. The Chair of Production Engineering of E-Mobility Components (PEM) and the Laboratory of Machine Tools and Production Engineering (WZL) at the RWTH Aachen University, focus on an integrated product and production development process. One of the declared overall research targets is to reduce the battery cost to less than 100 €/kWh on pack level. This paper determines the feasibility of engaging in a circular economy for the EV LIB market with the focus on a battery remanufacturing in the context of this Integrative Product and Process Development (IPPD) to reduce the production costs.

II. BACKGROUND

A. LIB in EV

The LIB technology is emerging as one of the optimum solutions for the middle-term future in energy storage of an EV. Typically, actual traction batteries consist of plurality of single battery cells. As visualized schematically in Fig. 1, these cells are first combined to a battery module and then these modules are assembled to a battery pack which is then integrated in the vehicles power train. Such battery solutions are highly cost-intensive not only due to the high material cost but also due to the various requirements, the long individual development process and the production costs [8]. Especially the safety features of the product must be fulfilled, to meet all the different standards and to guarantee a safe production process under high voltage [8]. It would be desirable to further reduce the production costs of LIB packs, to make the battery technologies available for a broad user range by affordable prices and to maximize the efficiency in battery production for all parties participating in the value chain. In this regard, it is still uncertain if and how the different Re-X (recycling,

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remanufacturing, reuse) strategies can affect the cost structures effectively [9].

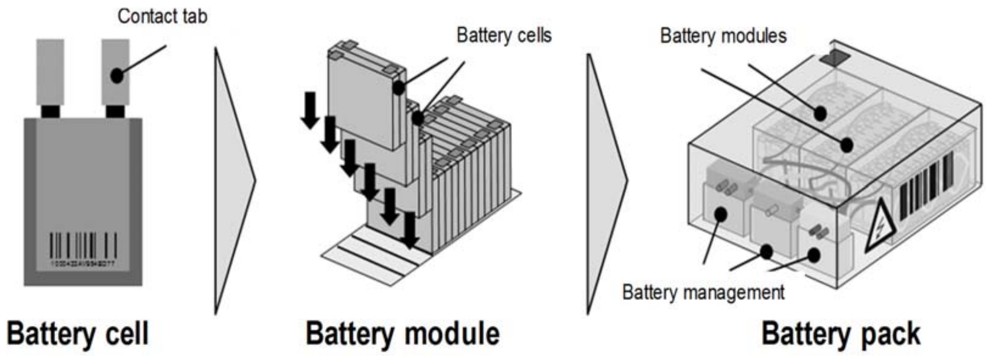


Fig. 1 From battery cells to a battery pack

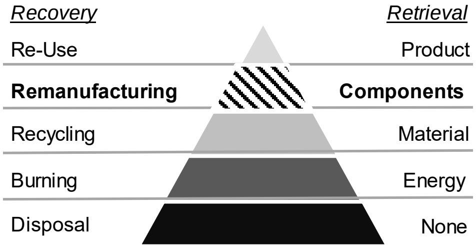


Fig. 2 Adapted waste pyramid – Higher level equals a better recovery efficiency [11]

Material scarcity puts additional pressure on the market leading to drastic price increases for materials involved in the production of LIBs [9]. The battery of an EV can account for up to 40% of the entire vehicle's value-added share; material cost is the leading expense in EV battery production [10]. This accounts for the depletion of resources having major economic repercussions on the industry. In order to offset the increasing costs incurred by materials prices, post-first life applications can lead to leaner technology production by maintaining the raw material in circulation. By remanufacturing and recycling the material efficiency can be increased.

B. Remanufacturing

Remanufacturing can be seen as the second best level of the adapted waste pyramid if you just consider the Re-X strategies besides prevention and minimization of waste. In comparison with the reuse, in which a complete product is transferred to a similar application or used in a different function and with the recycling, in which raw material is retrieved, remanufacturing focuses on the retrieval of individual components of an end-of-live product. This classification is visualized in the adapted waste pyramid and different Re-X strategies, Fig. 2 [11]. However, especially innovative industries face a lot of challenges on the way to the top of the waste pyramid. The electric mobility as a comparatively new market also faces a high cost pressure to produce the single components especially the battery more efficiently, to effectively increase the attractiveness of EVs [12]. Fast innovation cycles and the disruptive character of electric cars offer a high degree of freedom regarding innovative design for remanufacturing. This freedom allows functional updates to prolong the life time by improving the utility additionally to conventional reparation. Less power train components combined with an improved wear and a high efficiency form the basis for a prolonged life cycle of electric cars [12].

Remanufacturing as an industrial process to transfer a used and worn component in a quasi-new condition or to an improved functional condition increases the resource efficiency. But due to an optimized lifetime and material cost savings also the economic efficiency is higher [13]. The reuse of components retrieved by remanufacturing could therefore lead to a competitive cost structure for EVs. This is additionally amplified by different laws for a circular economy life-cycle which force companies to implement appropriate methods for a waste reduction to their product design. These laws tend to get stricter by time and intensify the urge to implement sustainable solutions in the product development process [14]. In comparison with refurbishing or retrofit, where single components are exchanged, updated or repaired, remanufacturing focuses on the complete product [15].

Various existing researches define product requirements to allow a remanufacturing. SUNDIN for example defines a serial production environment, replaceable components or the absence of disruptive technology changes as an enabler for a sustainable remanufacturing [16]. An EV fulfills all of those product requirements for a remanufacturing, but also the market, process and design requirements must be taken into consideration. The LIB is a fast-evolving technology and might face minor to medium disruptive innovations in the future [9]. For example, a different cell chemistry and design (Lithium sulfur or solid-state-batteries) or improved performance could affect the remanufacturing suitability so that a remanufacturing seems not preferable for vehicle batteries [9]. But due to an elaborate design for remanufacturing, which takes all requirements into consideration, for example by modular interfaces and replaceable components, the barrier of a disruptive character of the technology can be overcome [9].

The analysis of the different cost types such as material, labor but also capital costs for equipment and factory facilities prognosticates that a remanufacturing battery can be produced for around 60% of the initial cost of a new battery [17]. An example pilot process for remanufacturing of LIBs, known as cut-and-paste, has already been developed by Sybesma's Electronics and focuses on comprehensive battery testing, disassembly of post-vehicle-application batteries as well as the reassembly of remanufacturing batteries [5]. A similar remanufacturing process has been developed earlier just for consumer battery cells [18].

III. BUSINESS SITUATION FOR REMANUFACTURING IN ELECTRIC MOBILITY

For remanufacturing, various business models are conceivable. Some of them are already in practice and some seem promising for the emerging electric mobility market. Based on an overview of existing and conceivable applications the business situation for a remanufacturing of LIBs is framed.

A. *Remanufacturing in other industries*

In many industries, remanufacturing is already in use for single components especially in invest intensive areas such as industry machines, aerospace or plant construction [19]. In the automotive industry remanufacturing merely serves to improve the efficiency of the spare parts supply by automotive suppliers. For example, combustion engines, starters and alternators as well as clutches are predestined for remanufacturing [20]. All these components are obsolete in an EV.

B. *Potential Remanufacturing Applications for EV*

Up to now, in the automotive industry, only a refurbishing on component level is realized, which means that the car stays the same while changing or repairing wear parts. A remanufacturing on vehicle level is not implemented yet. One of the reasons is, amongst others, that the vehicle design concepts are not developed for and do not allow a disassembly and exchange of cost-intensive components [16]. The remanufacturing of cost-intensive components is not wanted due to design, environmental or safety aspects [17]. An integrated approach for a remanufacturing suitable design of the complete vehicle cannot be identified although it offers various economic and ecological potentials [17]. EV designs offer various levels of freedom for an integration of remanufacturing principles in the early product development process [21]. With their smaller number of components and a significantly reduced wear of those in comparison to a combustion engine powered car, remanufacturing requirements are targeted more effectively. On the level of a complete EV two different remanufacturing models are conceivable [12]. In comparison with a conventional vehicle, EVs can amortize the higher costs of acquisition due to their lower operating costs over life-cycle [12]. A longer usage of a vehicle is an approach to further improve this advantage. Especially fleet operators (e.g. in logistics) have a great interest in prolonging the life-time [22].

The short durability and the request for a modern up-to-date car can be addressed by a continuous update of the car, not only by software but also by hardware components. For this, the design of the car must be able to integrate new or remanufacturing components both in terms of product and process. The other variant is the remanufacturing of a complete EV for a dissimilar application. For example, an electric car produced for private use is remanufactured for a logistic use with exactly defined requirements which can be easily met by the remanufactured car. Therefore, for example the seats could be exchanged with transport racks and the battery capacity adapted to the needed operating range. Also for this model an elaborate design with modular interfaces and interchangeable components is needed. Especially the battery pack as the most valuable component of the power train is in focus of remanufacturing initiatives. Additional cost savings and a prolongation of life time is enabled by modular and intermountably designed battery packs, which allow a replacement of defective or outdated battery cells [9].

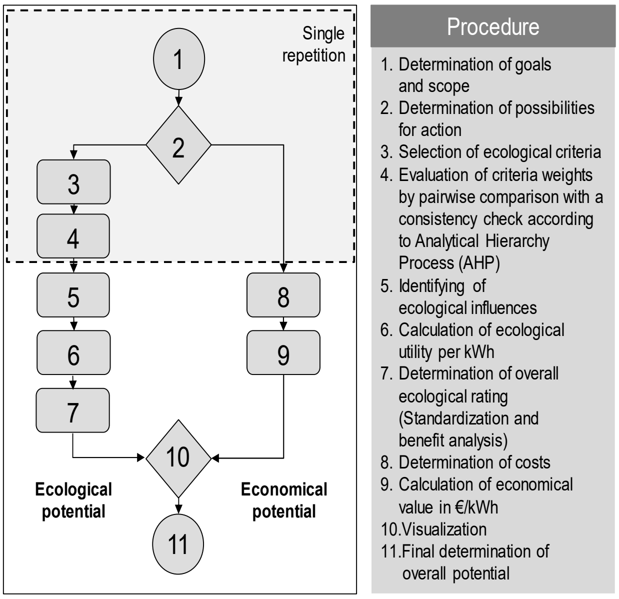
C. *Potential Remanufacturing Applications for LIB*

For the LIB pack, as the most valuable and properties-defining component of the EV, different use cases offer a rich potential for remanufacturing principles. First of all, the residual value (up to 70-75%) of used automobile batteries is still significantly high after the capacity dropped to just 80% and makes a reasonable usage in car unprofitable [23], [24]. Especially the cells but also the periphery modules such a housing, cooling or management system still are valuable enough for a remanufacturing process. Second-life concepts like a reuse as a stationary energy storage take this potential already in consideration. But due to very different requirements and conditions dissimilar application might not be the optimum solution [4]. Typically, the after-sales-market offers a high potential for remanufacturing solutions [20]. Considering the fast developing technology of LIBs, the industry faces new challenges for the after series supply of suitable battery packs. Especially for possible young timer cars with a long lifetime perspective (e.g. sport cars) a longer spare part supply is needed. Suitable remanufacturing solutions can help to establish a working spare part and after series supply of LIBs [12]. Furthermore, the durability of single cells in the battery pack varies strongly and affects the capacity of the complete pack. Changeable cells or modules in a remanufacturing design can help to improve the lifetime and reduce the range loss by time [9]. Taking the steadily improving battery technology in consideration updates for battery packs with new technology cells or modules are conceivable as well. Like this the possible range could be enhanced by time. Also, a modular range update, if the personal range requirements change, is a possible application for remanufacturing design.

D. *Business Model Assessment*

To address the different potentials, the business situation needs to be analyzed and a framework forms the basis for future market developments. Therefore, in analogy to

PORTER the customer, market, technology, competition and supplier situation must be examined [25].



1. Determination of goals and scope
2. Determination of possibilities for action
3. Selection of ecological criteria
4. Evaluation of criteria weights by pairwise comparison with a consistency check according to Analytical Hierarchy Process (AHP)
5. Identifying of ecological influences
6. Calculation of ecological utility per kWh
7. Determination of overall ecological rating (Standardization and benefit analysis)
8. Determination of costs
9. Calculation of economical value in €/kWh
10. Visualization
11. Final determination of overall potential

Fig. 3 Method for the impact and potential evaluation

The different customer segments for remanufacturing must be identified and their special requirements must be discovered in detail. Possible segments can be divided for example by the position in the supply chain, by the type of component, by the country, by the first or second life application or the deployed technology [20]. For those segments, special distributive channels must be identified and a possible price structure must be deduced. A positive market development and a deduction for a rising demand of remanufacturing batteries can be assumed by the projections for rising quantities of batteries used in EVs, the already high raw material prices and the limited available resource capacity especially for cobalt and lithium but also other rare, valuable metals [26]-[28]. To strengthen and deepen the market understanding different market shares, the global division, the market drivers and market boundaries must be identified. To identify the driving technology forces and possible enterprises for a market exploitation, it is mandatory to further analyze which technical and monetary capacities are necessary for the remanufacturing process of a LIB [17]. Furthermore, the identification of all potential *deal breaking* conditions reduces the entrepreneurial risk. An important question to solve is; which sort of company has the biggest potential in a new remanufacturing market. Is it inevitable to determine the product design or own intangible assets like an Original Equipment Manufacturer (OEM) or can start-ups generate benefits through their flexibility? For the supply situation, different variants of sources exist. The used batteries can be obtained directly from the vehicle user, the vehicle scrap yard or from the OEM. The uncertainties in quality, time and quantity of the returns are a great challenge for a successful remanufacturing business model [16]. The competitive situation in the remanufacturing market currently is unincisive. Entry barriers and regulatory boundaries exceed the achievable profits thus far.

IV. IMPACT AND POTENTIAL

To specify the benefits of a remanufacturing for LIBs a model for rating the ecological as well as the economical potentials was developed and applied. The method consists of eleven steps and can be divided into two parts. The first part (Steps 1-4) for weighting the criteria and select the data must be executed only once. The second part focuses on the assessment of the environmental and economic criteria and must be performed for each assessment.

The environmental assessment method to evaluate the ecological potential follows the requirements described in the standard DIN ISO 14044, where fundamental requirements like environmental relation, iterative approach or functional unity are described [29]. The different criteria are weighted against each other on the base of an Analytical Hierarchy Process (AHP) to allow an objective assessment [30]. The economic potential is evaluated on the data base of various research projects and industry numbers with the use of the net present value method (NPV), an investment appraisal and a cost comparison calculation [31].

To ensure the feasibility with existing data the following assumptions were made based on various sources [4]-[7], [18], [23]:

- Enough batteries in circulation
- Divisibility of battery capacity
- All collection, transport and remanufacturing processes takes place in Germany
- All batteries based on NMC cathodes

A. Ecological Potential of Remanufacturing LIB

For remanufacturing there is no ecological data of existing industrial processes available. The ecological benefits were calculated on a broad database from different research projects, which focus on the recycling, the second use and the assembly of LIBs [3]-[5], [17], [18], [23], [24], [32]-[33]. Parts of these processes are used in a remanufacturing process as well and build the foundation of the process calculation. For recycling the batteries run through a preparation and disassembly process. For the second use (e.g. in stationary energy storages) the batteries must be reconditioned and tested. And the last process for remanufacturing – the (re-)assembly – resembles an initial assembly. As an assumption based on the Mineta National Transit Research Consortium (MNTRC) research 10% to 15% of the cells need to be replaced for remanufacturing [5]. The results of these calculations are displayed in Table I and show a significant improvement by remanufacturing in all relevant sustainability factors. Especially the resource consumption and the greenhouse warming potential are improved by a remanufacturing process. To illustrate the criteria, the formula for the abiotic depletion potential for the consumption of resources of mineral type is presented in formula (1) [34]. ADP is the quotient of extraction rate of a resource and the square of the ultimate reserve of this resource. As for a remanufacturing, only a small amount of new resources is needed and in this scenario the components, which are not able to be remanufactured, are forwarded to a recycling process, the figure for the ecological impact in this category is slightly low.

$$ADP_{fossilEnergy} = \frac{DR_{fossilEnergy} \Big/ \left(R_{fossilEnergy}\right)^2}{DR_{ref} \Big/ \left(R_{ref}\right)^2} \qquad (1)$$

with

$R_{\text{fossil Energy}} \triangleq$ “ultimate Reserve” for fossil energy in MJ

$DR_{\text{fossil Energy}} \triangleq$ “De-accumulation” MJ/year

$R_{\text{ref}} \triangleq$ ultimate reserve of reference resource in kg

$DR_{\text{ref}} \triangleq$ extraction rate of reference resource in kg/year

TABLE I
ECOLOGICAL IMPACT OF REMANUFACTURING LIBS

Category	Indicator	Unit	Quantity
Consumption of resources	KEA	MJ/kWh	-224,1
	ADP	Kg-Sb-eq/kWh	-0,001
Greenhouse effect	GWP	Kg-CO_2-eq/kWh	-15,58
Eutrophication potential	EP	kg-PO_4-eq/kWh	-0,01
Acidification potential	SO2	Kg-So_2-eq/kWh	-0,09
Photochemical oxidants	POCP	Kg-Eth.-eq/kWh	-0,007

KEA = accumulated energy expenditures, ADP = abiotic depletion potential with an antimony equivalent, GWP = Greenhouse warming potential, EP = eutrophication of ecosystems, SO2 = Acidification potential with sulfur as reference substance, POCP = Photochemical oxidants with an ethene equivalent

B. *Economical Potential of Remanufacturing LIB*

The main economic potential for remanufacturing of LIB is the retrieval of battery cells and other valuable components such as housing, cables or electronics. To calculate the potential benefits, the costs for the disassembly and reassembly must be evaluated. A potential optimistic reselling price of 180 €/kWh for a remanufacturing battery is assumed based on similar calculations for second-life batteries in stationary energy storages [3]-[5]. This price also marks the upper limit for remanufacturing costs. The MNTRC already estimated the costs for a remanufacturing process of LIBs of a Chevrolet Volt with a capacity of 16 kWh [5]. The total costs for remanufacturing was estimated to 2.500 $ (~2250 €) which equals to costs of 140 €/kWh which results in a benefit of 40 €/kWh [5].

Taking a capacity loss to 80% (12.8 kWh) and an exchange of 10% defect cells (~720 €) into consideration the adjusted costs equal around 132,8 €/kWh [35]. Another cost driver are the personal costs (62,5 €/kWh) which are significantly high and can be reduced by an increased automation [5]. This would lead to a higher initial invest but cut be amortized by a higher quantity of batteries. For estimating an optimistic scenario by an automatic disassembly line, the assumptions from Table II were used for a capital expenditure budgeting calculation and the additional costs for a high automation disassembly line would be 19,44 €/kWh. Furthermore, the assumption is made, that personnel costs can be reduced to 30 €/kWh by optimization and economization due to the new assembly line. In total, it equals to a costs advantage of 13,06 €/kWh. The total costs sum up to 119,74 €/kWh. Compared to the assumed retail price in the scenario the total benefit of 60,26 €/kWh can be achieved by remanufacturing. However, for an economic success of remanufacturing for LIBs many challenges must be addressed, to make an automatic disassembly line profitable. High invest costs combined with low numbers of batteries cause a long amortization period. The complexity and quickly changing designs of the battery packs demand for a highly flexible technology. High voltage, explosion risks and electrolyte fumes are only a few hazards in disassembling a battery pack.

TABLE II
ADDITIONAL COSTS FOR AN AUTOMATIC DISASSEMBLY LINE

Category	Unit	Quantity
Invest for automation	€	6 million
Residual value at end of economic life	€	3 million
Economic life	Years	30
Interest rate	%	3
Variable costs	€/piece	96
Fixed costs	€/piece	150.000
Sales volume*	Pieces	30.000
Costs	**€/kWh**	**19.44**

*Car sales volume based on yearly production capacity of Renault ZOE

V. DESIGN FOR REMANUFACTURING IN LIB

A. *Design for Remanufacturing Principles*

To address the various potentials of remanufacturing for EVs and batteries, an elaborate holistic design of the components, which considers modularity, interfaces and disassembly, is required. The design principles are exemplarily shown on a LIB pack. Synchronized components of the module, the cell bracing and wiring and housing is the first key to a remanufacturing able design. Considering the workers’ safety (high voltage), the disassembly process is the main focus for gathering the design requirements. The changeability of cells must be guaranteed without any danger. Detachable connectors and wiring of the cells therefore becomes essential. The housing takes the role of a modular interface to insert the cells in a plug system. Ideally also the periphery (sensors, management, cooling) is pluggable and easy to connect. For this pluggable battery module, potential cost improvements were calculated. Here the additional benefit by the remanufacturing is not yet taken into consideration and would resolve in an even higher cost potential. Both changes could resolve to a cost reduction of 6% of the initial production costs each [36]. The plug-in system and its research needs are visualized in Fig. 4.

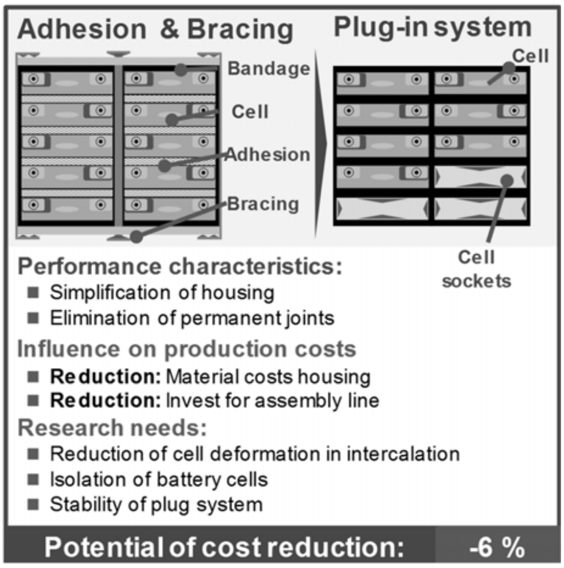


Fig. 4 Schematic presentation of a plug-in system [36]

B. Challenges to Be Addressed

To implement these design principles new design concepts and according business models need to be created, which acknowledge the high uncertainties and market scenarios. The vision of a working circular economy for LIBs with different second use application intensifies the pressure for industry wide arrangements for interface norms and modular standards. To address the challenges of uncertainties, special prediction models need to be developed which focus on quality, quantity and time of batteries available for a possible remanufacturing [12]. Furthermore, a method needs to be researched, implemented and validated which enhances the product development process with remanufacturing design guidelines considering uncertainties and business models [9]. As the disassembly is not the invers sequence of the manufacturing, a design for disassembly is essential. Moreover, the requirements for the following process steps for remanufacturing must be also considered in the design phase. The linkage of remanufacturing technologies builds the base for an itemization of design principles for each component. For example, many of the joining technologies used in battery production such as gluing or welding are challenging for a remanufacturing of LIBs of electric cars. For an early implementation of remanufacturing requirements in the development process it is necessary to find a global optimum in costs, quality and time. In the field of tension, the benefits of remanufacturing during the total life time must be set into context of the main requirements in the development process such as costs, weight, range or durability. In addition, the individual components' lifetime can be optimized on the best economic lifetime. The cell as main component could define the longest lifetime which exceeds the lifetime in the first-life usage. The components for which a replacement is anticipated can be designed for a much shorter lifetime. Modular interfaces and exchangeability can improve the production costs as requirements are lower with a planned obsolescence.

VI. CONCLUSION

A remanufacturing of LIBs used in electric cars offers potential for cost savings up to 60 €/kWh in an ideal scenario. In a functioning circular economy remanufacturing the batteries can improve the environmental impact in all relevant sustainability indicators, especially for the consumption of resources and the reduction of the greenhouse warming potential. In combination with second use and recycling activities remanufacturing improves the sustainability and reduces the production costs significantly. By elaborate design, which offers standardized interfaces and modularity, the barriers for remanufacturing a disruptive technology, such as LIBs, can be addressed and together with business models and carefully designed processes finally overcome. Due to an optimized design for remanufacturing further cost savings can be achieved additionally to the cost potential by the remanufacturing. The transfer and adaption of remanufacturing business models used in other industries and an optimized design for remanufacturing face various challenges. To address the challenges of uncertainties further research is necessary. Special prediction models need to be developed with focus on quality, quantity and time of batteries available for a possible remanufacturing. Furthermore, a method needs to be researched and implemented which enhances the product development process with remanufacturing design guidelines considering uncertainties and business models. A method to define a global optimum for costs, quality and time which includes remanufacturing needs to be designed, to overcome the technical and economic barriers and to create a fitting remanufacturing target corridor in the field of tension in the development process. Once this is accomplished a hardware demonstrator in a realistic test environment must be used to validate the findings.

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