Second-Life Battery Applications

Market potentials and contribution to the cost effectiveness of electric vehicles

Marco Rehme, Stefan Richter

IVM Institut für Vernetzte Mobilität gGmbH
Hohenstein-Ernstthal, Germany
marco.rehme@ivm-sachsen.de
stefan.richter@ivm-sachen.de

Aniko Temmler, Uwe Götze
Chair of Management Accounting and Control
Technische Universität Chemnitz
Chemnitz, Germany
aniko.temmler@wirtschaft.tu-chemnitz.de
uwe.goetze@wirtschaft.tu-chemnitz.de

***Abstract*—A fast market penetration of electric vehicles is (among other reasons) currently restricted by the high cost of batteries. Prolonging their life cycle by reusing them in other applications after they are retired from automotive service can be a viable option for addressing this problem. Decommissioned traction batteries still possess sufficient performance to meet the requirements of other mobile or stationary energy storage applications. This paper discusses possible secondary uses and their economic potentials.**

Keywords—electric vehicle batteries; secondary use; end-of-life-solutions; business models; value networks

I. Motivation

Electric vehicles (EVs) and integrating fluctuating renewable energies into the power system are key issues for a sustainable energy transition and for climate protection efforts. Despite federal, state and local authorities promoting the acquisition of electric vehicles and funding scientific research within this field, a successful market launch of electric cars largely failed to materialize thus far.

One of the biggest obstacles for a broad diffusion of electric vehicles is still the lack of economic efficiency in their usage when compared with conventional vehicles for average (and low) mileages. This is caused by higher initial investments (respectively depreciations) mainly due to the traction battery as the single most expensive component [1]. Therefore identifying and unleashing cost reduction or revenue potentials for electric vehicle batteries in all of their life cycle phases is of crucial importance.

Traction batteries reach the end of their first life when they do not meet the high requirements on power and energy density for automotive applications anymore. Usually that is the case after a 20 % loss of capacity, respectively 4,000 charge cycles or 8-10 years [2]. But then they are still suitable for energy storage uses with less demanding load profiles. A secondary use in an extended life cycle defers the technically complex, energy and cost consuming recycling process and can provide major contributions towards an economically efficient and sustainable energy supply. Second-life battery applications might reduce the life cycle costs of electric vehicles and even generate additional revenues.

To elaborate these opportunities this paper begins by describing the life cycle of traction batteries and its various stages (section II) before identifying and categorizing possible second-life applications in section III and assessing their market potentials in section IV. The paper concludes with a brief discussion of reasonable business models and possible roles for market players.

II. Life Cycle of Traction Batteries

A. Overview

The life cycle of traction batteries can be divided into five stages with two use phases representing their “two lives” in automotive and secondary usage [3]. Fig. 1 depicts these stages along with idealized patterns of the battery's general condition (blue line) and of battery lifetime value (red line).

The battery’s condition is measured by the State-of-Health (SOH), a figure of merit used to track cell degradation. Due to different electrochemical aging mechanisms in batteries and application-specific requirements, the SOH can be derived from a variety of performance parameters like capacity, internal resistance, voltage, self-discharge and charge acceptance, while it is normally defined as the ratio between actual capacity and nominal capacity [4].

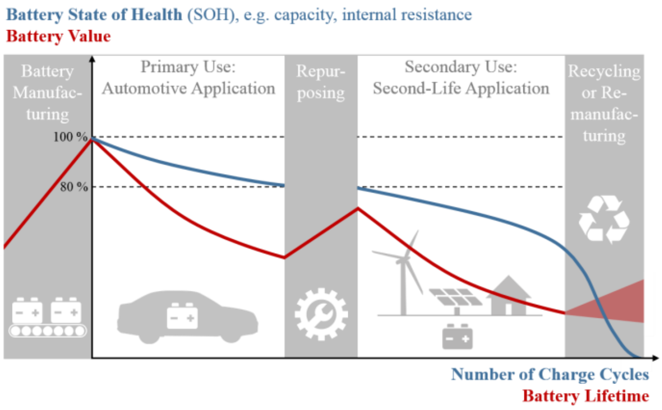

Fig. 1. Life cycle of traction batteries.

As measurement for the ability to deliver the specified performance compared to a new product, a battery's SOH typically will be 100 % at the beginning of its first use phase and deteriorate gradually with an increasing number of equivalent full charge cycles due to irreversible physical and chemical changes. As shown in Fig. 1, the SOH is also an indication of the point that has been reached in the battery's life cycle since it decreases over use and time until eventually the battery is no longer suitable for specific (more demanding primary or less demanding secondary) applications. With Li-ion batteries (as state-of-the-art technology for EVs) highly nonlinear aging characteristics (accompanied by a sudden drop in capacity and preventing a further use) will occur at some point in the life cycle [5], as depicted in Fig. 1.

The battery value (like any other product value) can be derived by a cost-based or a revenue-based approach. The use of factor inputs (labor, capital, raw materials, energy etc.) in production processes (as part of battery manufacturing and repurposing) increases its value while steady usage and the passage of time decreases it [6]. A specific major cause for the time-related decline in battery value will be the expected drop in the price of new batteries due to technical advances, higher production rates and economies of scale within the next years [7]. Usually cost-incurring activities are only executed if there are enough customers with a sufficient willingness to pay for the output. Nevertheless, in the case of (traction) batteries recycling processes may be performed even without economic efficiency if they are imposed by statutory requirements. So the revenue-based value might possibly decrease during the recycling process.

The following subsections will briefly describe the distinct life cycle stages with their characteristic activities and processes.

B. *Battery Manufacturing*

The presented battery life cycle refers to a single product unit and therefore implies that corresponding preliminary activities like technology development, product design and market preparation already took place previously. Battery manufacturing itself is a highly complex production process based on the procurement and handling of raw materials and comprising a vast number of individual process steps at different hierarchical hardware levels (cell, module, pack and system). The cell manufacturing process can be divided into three main production steps: electrode fabrication, cell assembly and cell formation [8]. Paste mixing, coating, drying and calendering are examples for sub-processes of fabricating electrodes. Manufactured cells are connected and packaged in module, pack and system assembly processes integrating also sensors, cables, the cooling and the battery management system. Depending on cell types and pack configurations different joining methods come into consideration. The final step before a traction battery can start operating in its primary use is the wiring and integration of the battery system into an electric vehicle powertrain. Several logistics processes accompany cell production, hardware assembly and vehicle integration, especially when they are performed by different and spatially separated market players.

C. *Automotive Application*

A traction battery's first use phase consists of providing electrical operating power for the motor and the auxiliary units of an EV whenever needed and possibly of providing storage capacity for "smart" power grid services (*vehicle-to-grid*) in addition to that. It is characterized by a sequence of recurring processes of charging and discharging which can vary considerably over time and between vehicle users depending on individual usage profiles and driving habits. The first life of a traction battery ends, when it reaches a condition that no longer meets the requirements of vehicle operation. That is the case when the decrease in the battery's performance reduces vehicle range and acceleration beyond an acceptable level. Usually a SOH of about 80 % is defined as criteria for the occurrence of this state of degradation and the end of the first life [2], [7]. When the battery is no longer suitable for the automotive application, it has to be replaced by a new one and is available for secondary uses. However it has to be repurposed for this objective before.

D. *Repurposing*

Enabling a traction battery to serve a new purpose involves several activities. Initially it has to be removed from the electric vehicle powertrain. Depending on the secondary use it will be disassembled to smaller hardware levels (packs or modules). The deeper the level of dismantling is, the higher the costs incurring will be. So disassembly will only be performed to the extent necessary for the intended new purpose and maybe even omitted for large energy storage solutions. Battery units in the desired level of disassembly have then to be tested for functionality and their current aging condition has to be determined. Today SOH determination of single units is one of the main cost drivers in repurposing processes, because in most cases the corresponding values cannot be read out from the battery management system easily but have to be measured at great expense [7]. The availability of SOH quick tests is crucial for the feasibility of second-life concepts. By means of the determined SOH values of battery units their suitability for specific applications can be assessed. Eventually, units that are in a sufficient and similar condition will be cleaned, adjusted, refurbished and reassembled to battery systems in dimensions that are needed to meet the requirements of the particular second-life application. Once more the final step before battery commissioning is the integration into the new technical system. Furthermore, repurposing is also accompanied by reselling and logistics activities that facilitate a commercial exploitation.

E. *Second-Life Application*

The usage of a former traction battery in its second life is again characterized by more or less frequent sequences of charging and discharging. In contrast to its automotive first life the differences between specific usage profiles and operation schedules is much larger than with powering an EV as a common basic application. Possible second-life applications differ widely, not only in energy storage dimensions, but also in their purpose and their field of use. Some aim at a permanent use, others for an emergency or back-up supply. Some are for mobile and others for stationary fields of use.

Section III will present a general view of conceivable applications. As with its primary use, the battery will finally reach a condition that makes it unfit for further use in the current application. Another repurposing for a theoretically possible third life will usually be uneconomic, so that the battery has to be sent to recycling facilities at this point in the life cycle [7].

F. Recycling or Remanufacturing

EU legislation mandates the collection and recycling of waste batteries and prohibits their simple disposal in landfill sites or by incineration [9]. The purpose of recycling is on the one hand minimizing the negative impact of hazardous waste on the environment, thus contributing to its protection and preservation, and on the other hand salvaging valuable raw materials. Basically, many elements contained within batteries like lithium, nickel, copper and cobalt can be salvaged to a great extent by the help of several mechanical and chemical methods. Relevant activities and processes of recycling involve collecting, sorting and separating the peripheral equipment, disassembling, mechanical reprocessing, pyrolysis and gas treatment, hydro- or pyrometallurgical treatment, refining and the disposal of residual materials, as well as supplemental processes of distribution and logistics [10]. With the reuse of recovered raw materials in new (battery) manufacturing processes the material cycle closes. Achievable recycling revenues depend on highly volatile commodity prices. Despite the valuable resources contained in batteries, their recycling is not economically efficient under current conditions due to the energy-intensive sub-processes of existing recycling technologies [7]. But this might change in future. An alternative to recycling at the end of the second life (as well as to repurposing at the end of the first life; for simplicity not depicted in Fig. 1) is remanufacturing, which means restoring the condition of a battery to meet the applications requirements by replacing faulty cells within a battery.

III. Possible Second-Life Applications

A. Overview

After reaching their critical SOH for usage in electric vehicles, traction batteries may continue to live as energy storage systems in several second-life applications. Regarding the secondary marketing of EV batteries different market participants can be identified, such as electricity producers, grid operators, vehicle and battery manufacturers, disposal companies, consumers and service providers (e.g. for charging stations and storage pools). Based on the perspective of potential operators, a broad range of second-life applications has been systemized. The resulting Fig. 2 illustrates a variety of application scenarios which may be currently of particular interest from both the provider's and the user´s perspective. According to the degree of mobility, this overview focuses on the following three categories: stationary, quasi-stationary and mobile application scenarios, whereas stationary scenarios can be further differentiated between on-grid solutions (with connection to the distribution network) and off-grid solutions (non-connected) [3], [11].

Second-Life Applications						
Stationary application scenarios	***On-grid solutions*** (network-connected)					
	Perspective of the operator	(Industrial) plant operators	Storage operators		Charging infrastructure operators	Residential and commercial real estate owners
	Applications	Short-term storage systems for renewable energy production plants (wind power and photovoltaics)	Stationary storage systems for participating in electricity balancing markets	Short-term storage systems for grid stabilization and regulation	Storage buffers for DC-quick charging stations	Storage systems for load shifting energy-intensive consumers (load management)
	Off-grid solutions (without network connection)					
	Perspective of the operator	(Small) plant operators/private households		Operators of critical infrastructure	Storage/charging infrastructure operators	
	Applications	Storage systems for optimizing the own consumption of electrical energy from photovoltaics	Storage systems for uninterruptible power supply of private households	Emergency power systems for ensuring security of supply	Autarkic storage systems for micro mobility (e.g. charging e-bikes in non-grid-connected areas)	
Quasi-stationary application scenarios	***Off-grid solutions*** (without network connection)					
	Applications	Decentralized energy supply of major events	Decentralized energy supply of construction sites			
Mobile application scenarios	***Industrial solutions***					
	Applications	Re-use in industrial trucks (e.g. forklifts, lift trucks, tractors, transport trolleys), sweepers etc.	Re-use in driverless transport vehicles for the internal transport			
	Private and commercial solutions					
	Applications	Re-use in e-bikes, e-scooters, golf carts etc.	Battery swapping systems for e-bikes, e-scooters	Re-use in driverless transport vehicles		

Fig. 2. Overview about possible second-life applications.

B. *Stationary application scenarios*

1) *Gridable-/On-grid solutions*

Stationary storage systems in on-grid solutions serve, among other things, to stabilize the electricity grid. In the context of energy transition, increasingly fluctuating energy sources such as photovoltaics and wind power stations are connected to the electricity grid [12], [13]. In order to buffer surplus energy, to feed it back into the power grid in times of high energy demand (with high network utilization and high prices for remuneration) and, as a consequence, to reduce load peaks, it is important to establish stationary storage systems for the peak load management of (industrial) plant operators. Here, discarded traction batteries (bundled to large battery packs for grid support) can be implemented for re-use [14].

Additionally, second-life batteries can be used in the primary balancing power market for maintaining the frequency stability of electricity grids. In this matter the batteries not only contribute to grid stability, but also increase attractiveness of the emergence of new market participants. Thus, storage managers or rather storage pool operators could absorb electric energy in the short term, buffer it in pooled batteries (which are particularly suitable due to their short activation time) and release the energy in the short term again. For these activities a storage manager could receive appropriate monetary remunerations. Due to the necessary minimum offer size of ± 1 MW it is also essential to aggregate a big number of traction batteries [7], [15].

A similar business segment is opening for the application of batteries as short-term storage systems for stabilizing and regulating the electricity grid. In network-critical situations, production surpluses can be buffered, energy feeding peaks can be straightened and the re-dispatch of generating plants according to § 13 EnWG can be avoided [16]. A joint venture consisting of Daimler Automotive, The Mobility House and the GETEC Group is currently working on a battery storage system in the megawatt range that is intended to be used in this field of application. Composed of about 650 traction batteries, the storage will be built in Lunen (North Rhine Westphalia) with the aim of compensating strong network supply variations [17]. Similar efforts can be currently observed in other companies of the automotive sector, such as General Motors, Mitsubishi, PSA Peugeot-Citroën or Nissan, to name but a few.

Discarded traction batteries could be also of interest for charging infrastructure operators. In order to achieve (at least approximately) the objective of one million electric vehicles until 2020, the National Electric Mobility Platform (NPE) is calling for a massive expansion of the charging infrastructure [18]. Regarding this, quite a number of DC-quick charging stations are expected to be built, thus placing an additional burden on the grid due to their delivery of high loading performance. By deploying storage buffers for the DC-quick charging stations, potentials of load transfer and reduction can be fully exploited, power peaks can be straightened and consequently the purchase costs per kilowatt-hour can be reduced [19]. At the end of 2014, Vattenfall in cooperation with Bosch and the BMW Group started a pilot project in Hamburg. In this context quick charging stations have been equipped with storages from discarded BMWi traction batteries for relieving the grid. Additionally, in further sub-projects a 2 MW-mass-storage (also consisting of old BMW traction batteries) shall be developed for future usage in the primary balancing power market as well as private households shall be provided with storage systems for optimizing the private consumption of electrical energy [20], [21].

By analogy with DC-charging station storage buffers, second-life batteries can also be used for load shifting of energy-intensive consumers. After equipping residential and commercial units with storage systems and connecting them to the grid, private households and commercial premises owners will be able to buffer surplus renewable energy (for instance from photovoltaics) and to benefit from their self-generated (or from third-party generated) buffered energy in peak times.

2) *Off-grid solutions*

In addition to grid-connected stationary storage systems, traction batteries are also particularly attractive for application in decentralized (off-grid), small to medium sized storages [22]. Especially in issues such as “smart home” and “energy autonomous living”, storage systems are of special interest for optimizing the own consumption of electrical energy from photovoltaics. By coupling the photovoltaic systems with battery storages, excess energy can be buffered and used in peak times respectively during periods of reduced solar radiation. Considering the continuously declining EEG (Renewable Energies Act) compensation and due to the fact that since 2011 the feed-in tariff for electricity is below the retail price of electricity for households, nowadays, photovoltaics combined with storage systems are more attractive than ever [7]. This effect will increase even further with the expiry of the EEG compensation [22].

Furthermore, traction batteries can be re-used in autarkic storage systems for micro mobility (e.g. for providing energy in non-electricity connected areas), in storages for uninterruptible power supply of private households as well as emergency power systems to ensure the availability of electricity for critical infrastructure (for instance hospitals, public transport companies, data centers etc.) [7].

C. *Quasi-stationary and mobile application scenarios*

Besides the stationary applications, it is also possible to integrate traction batteries after their end of life in electric vehicles for second usage either in quasi-stationary concepts (e.g. for decentralized energy supply of major events or construction sites [11]) or exclusively in mobile solutions.

Re-using the batteries in vehicles with lower power and performance requirements compared to the first use requirements in electric vehicles, is particularly attractive since a reprocessing of batteries is hardly or not at all necessary. In the mobile application, both industrial and private or commercial solutions are conceivable. Due to the high degree of electrification of approximately 70 %, industrial trucks (for instance forklifts, lift trucks and transport trolleys) constitute a potential medium for discarded traction batteries [12]. Moreover, second-life batteries could be appropriate for an application in sweepers and driverless transport vehicles. In the private and commercial sector traction batteries can be re-used after losing their capacity of more than 20 % in minor motorized EVs such as e-bikes, e-scooters, golf carts etc., thus making a valuable contribution to sustainable energy supply.

The selection of the favored second-life application depends on a variety of underlying conditions. Among detailed information about battery history (battery status, residual capacity, internal resistance, number of passed cycles, depth of cycles etc.) and battery chemistries, the dimensions of storage systems (the number of the battery packs needed) as well as safety and reliability demands are quite important [2], [23]. In particular, the limited availability of discarded traction batteries might restrict the second use in packs for larger applications. Whereas small photovoltaics with average power range are just equipped with 2-10 kWh batteries, the demand of a battery volume from 300 up to 1,000 kWh for storage systems in larger photovoltaics (with installed power of ± 1 MW) is a critical dimension for an exclusive utilization of second-life batteries [12]. In comparison, the prototype of a storage in energy-efficient houses is composed of 7,250 individual used battery cells with a total storage capacity of 40 kWh [24]. Even in mobile application scenarios the required battery size can vary widely. Whereas small machines partly get along with batteries in a dimension of 0.2 kWh, for instance a larger counterbalance fork-lift truck needs more than 80 kWh batteries. Safety and reliability risks play a key role, especially when using discarded batteries in large applications and critical infrastructures. Thus, large applications with many battery packs are associated with a higher risk of fire and explosion than smaller ones. Additionally, the utilization of second-life batteries for ensuring security of energy supply in critical infrastructures should be regarded as critical, because discarded batteries do not necessarily fulfill the increased safety requirements (high level of reliability) [12].

IV. Market Potentials of Second-Life-Battery-Solutions

A. *Defining market potential*

There are two important prospects for determining market potentials of second-life batteries. First, the need for storage solutions, which denotes the market potential for these batteries. This demand side of second-life batteries is influenced by, amongst others, costs and usability of other storage technologies. Second, the amount of available second-life batteries at certain time, which is dependent on the market diffusion of EVs. This supply side delimites the market potential of second-life batteries.

The total market potential of EVs in Germany can be traced back to the total stock of vehicles which are published by the German Federal Motor Transport Authority (KBA). However, the electrification of the – at present more than 44 million [25] – vehicles will be gradual over several decades. This gets obvious by the objectives of the German government addressing one million EVs for the year 2020 and six million EVs in 2030. Hence, the previous and future market diffusion is a decisive factor for the temporal availability of second-life batteries. In the following, it is attempted to estimate the market potential of second-life batteries in Germany. In order to build upon existing and accessible data, we decided to estimate the market potential from the supply side until the year 2028.

B. *Description of methods, data and assumptions*

The estimation of the market potential of second-life batteries requires a valuation of their number, size and time of availability. The time of availability is decisively influenced by the yearly amount of new registrations of EVs as well as the useful life in the automotive application period. Due to this, we firstly analyzed the stock of EVs and Plug-in-Hybrid electric vehicles (PHEV) according to the KBA for the years 2009 until 2015, to quantify the current market penetration. Both types, EVs and PHEVs, were summarized as Plug-in-Electric vehicles (PEV). Additionally, we estimate the future development of PEVs stock until the year 2020 and focused on three scenarios by using trend extrapolation and existing research studies, as shown in Fig. 3 and described below:

1. Reference-scenario: Is a trend extrapolation of the real PEV stock by quadratic extrapolation.
2. Medium-scenario: Takes additional parameters into account, such as willingness to pay, costs of infrastructure and limited availability of PEVs.
3. Monetary policy-scenario: Contains the introduction of a special depreciation (for commercial use of PEV) and a price subsidy of 500 euros (for residential and commercial use) from 2018.

Market diffusion by scenario two and three are based on a simulation model that was developed by the Fraunhofer Institute for Systems and Innovation Research ISI and is used by the NPE. The assumptions of the simulations conducted by ISI [26], [27] are kept for this study. The particular relevance of scenario three results from the current political discourse about achieving the national objectives for the EV penetration rate in 2020 by introduction of policy measures.

For the modeling of battery sizes, we have assigned presently available and (for the near future) advertised PEV models into four segments (small, medium, large and others). To estimate future EV battery sizes we used the assumed development of battery sizes from [27].

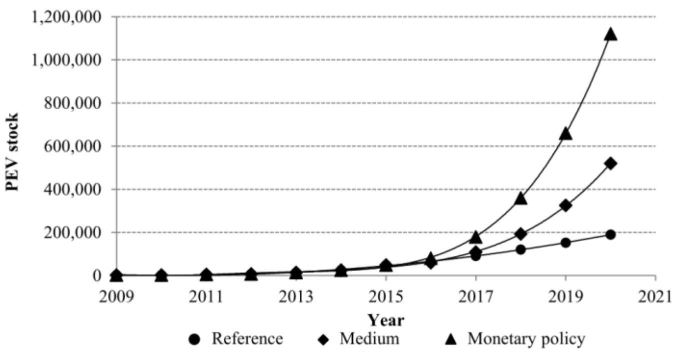

Fig. 3. Scenario based development of the German PEV stock.

Based on these aggregations and assumptions, we have generated arithmetic averages of battery sizes for each segment and year in order to estimate the yearly amount of battery capacity in EV stock.

As we discussed, irreversible capacity losses result from the calendric and cyclic degradation of battery cells. The degradation processes of different battery technologies are not completely investigated. Furthermore, at the moment no reliable findings regarding the useful life of PEV batteries in the automotive application period do exist. Scientific studies have quantified the end of life in automotive application, for example, in a range of five and ten years until they reach irreversible capacity losses between 20 and 30 % of their initial capacity [23], [28], [29]. Therefore, we simplifying assume that the optimal replacement time of PEV batteries is, on average, after eight years of automotive use at a SOH of 80 %. According to HEYMANS et al. [23], these assumptions are corresponding to usual manufacturers' warranties and industrial targets for battery longevity. Correspondingly, eight years after the beginning of automotive use is the earliest time for second-life applications.

C. Results

Depending on the particular market diffusion scenario, the total market potential of second-life batteries can be rated in a range of 12.88 GWh to 44.15 GWh until the year 2028. Due to the already accomplished development of the PEV stock until 2015, we can quantify a maximum of 939 MWh for the end of the year 2023. However, sizeable quantities of battery capacities can be expected from the year 2026 on, as illustrated in Fig. 4.

The wide spread of available battery capacities after 2023 results from uncertainty of future market development of PEV including the type of vehicles (vehicle segments). In the final analysis, we estimate the market potential for the year 2028 at a minimum of 4.15 GWh, in accordance with the reference scenario, and a maximum of 19.55 GWh, referring to the monetary policy scenario.

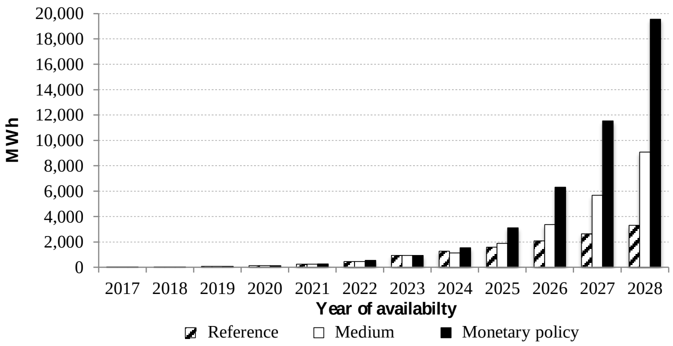

Fig. 4. Yearly availability of second-life batteries, valued in Megawatts per hour (MWh).

D. Limitations

In addition to the calculated market potentials, it has to be noted that our results indicate a maximum potential from an economic perspective. Technical limitations, such as premature defaults during automotive application period, the suitability of battery type or technology, as well as disproportional irreversible capacity losses are not implicated. Previous research estimates the economic amount of second-life batteries of about 35 % of the total annual market potential [30].

V. DESIGN OF FUTURE BUSINESS MODELS

A. Introduction

New disruptive technologies and transforming processes enable market entrance for innovative companies or even the emergence of new market roles. In addition, there are opportunities and risks for established enterprises. Based on market observation, we see actually two options for the implementation of sustainable and financial attractive business models in the context of second-life battery applications.

Referring to KLÖR et al. [31], the basic market design can be distinguished between an open, closed or intermediate market. Following on this differentiation, we have adapted the open and closed market framework to new business models for second-life battery applications. In the following section we briefly discuss the configuration of the organizational framework, specific advantages of these models and relevant agents which should be involved in the respective second-life business model.

B. Integrated business model in a closed battery market

Currently, the value chain of batteries is determined by a few companies, e. g. suppliers of battery-materials/cells and battery modules/systems or automotive manufacturers (OEM). In the course of the construction of the Gigafactory, the OEM Tesla Motors Inc. will expand its activities to include more upstream processes. Due to existing competencies in this field, OEMs may also provide additional activities. By the following integrated business model, we give a suggestion, to include second-life battery applications into the value chain processes of an OEM.

While established OEM prospectively can lose their influence in the value chain of the EV, diversification and vertical integration of activities, in context with the lifecycle of traction batteries, can cause compensation effects. Fig. 3 outlines a framework for a potential integrated business model of an OEM, by the implementation of new process (incl. second-life usage) into the existing organizational structure.

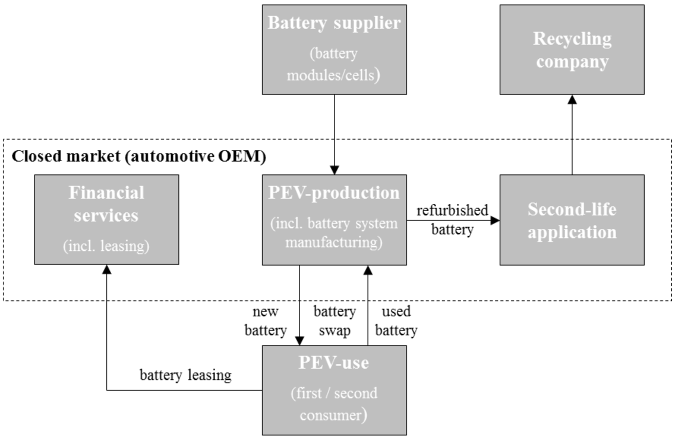

Fig. 5. Integrated business model framework for automotive OEM.

In the proposed framework, the OEM operates as a focal enterprise within the value chain of traction batteries retaining ownership of battery systems during the period of automotive usage and controlling the most important processes within the battery lifecycle. This affects the production of battery systems or battery modules through subsidiaries (e. g. Deutsche ACCUmotive GmbH & Co. KG for Daimler AG) as well as integrated financial services to the consumer (battery leasing) by existing business units (e. g. Volkswagen Leasing GmbH, Mercedes-Benz Bank AG etc.). Battery cells are still provided by the external battery supplier. Battery swapping – at the end of automotive usage – could be organized by downstream industries, for example by car dealers or authorized repairers. Second-life battery usage requires the development of new organizational units, depending on the realized application scenario. Conceivable solutions may address the reduction of energy costs in production plants or the expansion of business into new markets, such as the management of storage solutions (e. g. for charging stations or storage systems for ancillary services etc.). As the second proposal could generate additional revenues, this approach may be more worthwhile for automotive OEM.

Besides the advantages for the OEM, such as the increased amount of vertical integration, new business areas and the monitoring of key battery parameters during the period of automotive usage, decisive benefits can result for the end consumer. Due to battery leasing, the OEM retains ownership of the battery system enabling the decrease of initial costs of the PEV-user. In addition, a battery swap at the end of first life (fixed by number of charging cycles or useful life) could increase the acceptance of PEV-users and set additional incentives to buy a PEV.

C. Multi agent business model in a open market

Unlike the integrated business model, an open market design allows trading and resale of used tractions batteries and thus opens opportunities for a competition among several agents. An important difference to the integrated business model is the emergence of the battery manager as a new market role and the ownership of the battery system, as illustrated in Fig. 6.

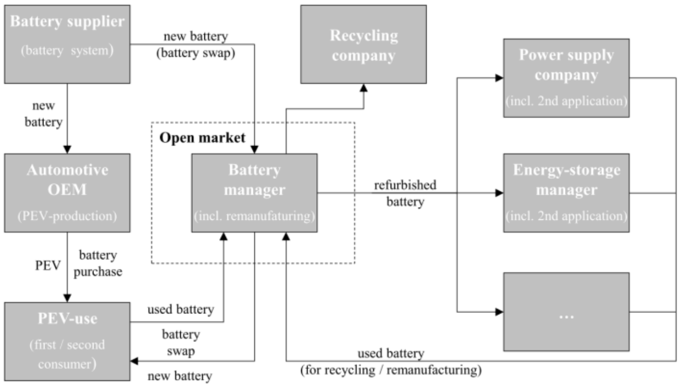

Fig. 6. Business model framework in a multi agent prospective.

Regardless of OEM-activities, the battery manager handles important processes that occur among primary and secondary use of batteries, in particular swapping, repurposing, remanufacturing and distribution of used and refurbished battery systems and finally the recycling after the period of second-life usage. In addition to technical and logistics competencies, the battery manager is also familiar with trading activities (purchase from car owner and resale to second-life user). Its market role could be taken by companies at least from two industries with relevant expertise or by business partnering of both (e. g. joint venture): First, the battery supply industry – due to knowledge in the field of commercialization of battery systems; or second, the recycling industry – due to knowledge of circular economy.

Secondary uses can be executed by a variety of specialized agents, in context with storage solutions for ancillary services in energy market, storage systems for private households or micro mobility (see section III). Therefore, second-life battery users could buy refurbished batteries on an open market with market based pricing.

The future will show what types of second-life applications will be suitable and (economically) feasible solutions, especially with regard to their quantity and the kind of realized business model. There is a strong need for further research, as a result of limited data availability and empirical experiences with degradation processes of EV batteries.

ACKNOWLEDGMENT

This work was supported by the European Union (European Social Fund; ESF), the Sächsische Aufbaubank (SAB) and the Free State of Saxony within the junior research group ECoMobility − Connected E-Mobility and within the promotional program Electromobility Connects (Bavaria-Saxony), which is one of four showcase regions in Germany to support electric mobility. Any views expressed herein are those of the authors and do not necessarily reflect those of the funding bodies or partners involved in the projects.

REFERENCES

[1] C. Linse and R. Kuhn, “Design of high-voltage battery packs for electric vehicles”, in B. Scrosati, J. Garche and W. Tillmetz, Eds., Advances in

Battery Technologies for Electric Vehicles. Cambridge: Woodhead, 2015, pp. 245-264.

[2] D. Beverungen et al.: „End-Of-Life Solutions für Traktionsbatterien (EOL-IS)“, in D. Beverungen, C. Fabry, W. Ganz, M. Matzner, G. Satzger, Eds., Dienstleistungsinnovationen für Elektromobilität: Märkte, Geschäftsmodelle, Kooperationen. Stuttgart: Fraunhofer-Verlag, 2015, pp. 52-75.

[3] J. Neubauer and A. Pesaran, NREL’s PHEV/EV Li-ion battery secondary-use project, National Renewable Energy Laboratory Conference Paper NREL/CP-540-48042, June 2010.

[4] J. Garche, Ed., Encyclopedia of Electrochemical Power Sources. Amsterdam: Elsevier, 2009.

[5] S. F. Schuster et al., “Nonlinear aging characteristics of lithium-ion cells under different operational conditions”, in Journal of Energy Storage 1 (2015), D. U. Sauer, Ed. Amsterdam: Elsevier, 2015, pp. 44-53.

[6] G. Siestrup, Produktkreislaufsysteme: Ein Ansatz zur betriebswirtschaftlichen Bewertung produktintegrierter Umweltschutzstrategien in kreislaufwirtschaftsorientierten Produktionsnetwerken. Berlin: Erich Schmidt Verlag, 1999.

[7] S. Fischhaber, A. Regett, S. F. Schuster and H. Hesse, Studie: Second-Life-Konzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen Analyse von Nachnutzungsanwendungen, ökonomischen und ökologischen Potenzialen, Ergebnispapier 18 der Begleit- und Wirkungsforschung. Frankfurt am Main, 2016.

[8] H. Berg, Batteries for Electric Vehicles: Materials and Electrochemistry. Cambridge: Cambridge University Press, 2015.

[9] Directive 2006/66/EC of the european parliament and of the council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC.

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

[11] D. Beverungen and D. Schulte, “EOL-IS: End-Of-Life Solutions für eCar-Batterien – Entwicklung integrierter Lösungen und Informationssysteme für die Weiterverwendung von Traktionsbatterien aus Elektrofahrzeugen“, URL: http://www.eol-is.de/sites/www.eol-is.de/files/u5/News/EOL-IS%20-%20Folder%20-%202015.pdf, 2015.

[12] T. Schlick, B. Hagemann, M. Kramer, J. Garrelfs and A. Rassmann, “Zukunftsfeld Energiespeicher − Marktpotenziale standardisierter Lithium-Ionen-Batteriesysteme“, URL: http://www.rolandberger.de/media/pdf/Roland_Berger_Zukunftsfeld_Energiespeicher_20120912.pdf, 2012.

[13] M. Bauer, “E-Auto-Batterien im zweiten Frühling“, URL: http://www.eurotransport.de/news/stationaerer-speicher-e-auto-batterien-im-zweiten-fruehling-6784363.html, November 2015.

[14] G. Lacey, G. Putrus and A. Salim, “The use of second life electric vehicle batteries for grid support”, in Proceedings of the IEEE EuroCon 2013, Piscataway NJ, pp. 1255-1261.

[15] Verband der Netzbetreiber e.V. (VDN) beim VDEW, “TransmissionCode 2007 Anhang D3 – Unterlagen zur Präqualifikation für die Erbringung von Minutenreserveleistung“, URL: https://www.bdew.de/internet.nsf/id/A2A0475F2FAE8F44C125783000 47C92F/$file/TransmissionCode2007.pdf, August 2007.

[16] D. Fürstenwerth and L. Waldmann, “Stromspeicher in der Energiewende: Untersuchung zum Bedarf an neuen Stromspeichern in Deutschland für den Erzeugungsausgleich, Systemdienstleistungen und im Verteilnetz“ Studie der Agora Energiewende, URL: http://www.agora-energiewende.de/fileadmin/downloads/publikationen/Studien/Speicher_in_der_Energiewende/Agora_Speicherstudie_Web.pdf, September 2014.

[17] The Mobility House, “Daimler bringt mit The Mobility House Speicher ans Netz“, URL: http://mobilityhouse.com/de/daimler-bringt-mit-the-mobility-housespeicher-ans-netz/, Mai 2015.

[18] Nationale Plattform Elektromobilität (NPE), “Ladeinfrastruktur für Elektrofahrzeuge in Deutschland – Statusbericht und Handlungsempfehlungen 2015: AG 3 – Ladeinfrastruktur und Netzintegration“, URL: http://nationale-plattform-elektromobilitaet.de/fileadmin/user_upload/Redaktion/NPE_AG3_Statusbericht_LIS_2015_barr_bf.pdf, Berlin, November 2015.

[19] A. Kampker, A. Schnettler and D. Vallée, “Elektromobilität – Grundlagen einer Zukunftstechnologie“, Berlin, Heidelberg: Springer-Verlag, 2013, DOI 10.1007/978-3-642-31986-0.

[20] Vattenfall, “Das zweite Leben der E-Mobility-Batterien“, URL: http://blog.vattenfall.de/das-zweite-leben-der-e-mobility-batterien/, August 2015.

[21] BMW Group, “BMWi Batterien werden als “Second Life Batteries“ flexible Speicher für erneuerbare Energien und sichern die Stabilität des Stromnetzes“, URL: https://www.press.bmwgroup.com/deutschland/pressDetail.html?title=bmw-i-batterienwerden-als-second-life-batteries-flexible-speicher-für-erneuerbare-energienund&outputChannelId=7&id=T0193200DE&left_menu_item=node__6728, September 2014.

[22] Fraunhofer ISI, “Gesamt-Roadmap Stationäre Energiespeicher 2030“, URL: http://www.isi.fraunhofer.de/isi-wAssets/docs/t/de/publikationen/GRM-SES.pdf, Karlsruhe, Dezember 2015.

[23] C. Heymans, S. B. Walker, S. B. Young and M. Fowler, “Economic analysis of second use electric vehicle batteries for residential energy storage and load-levelling,” Energy Policy 71, 22-30, 2014.

[24] BMUB Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, “Wege zum Effizienzhaus Plus“, URL: http://www.bmub.bund.de/fileadmin/Daten_BMU/Pools/Broschueren/effizienzhaus_plus_broschuere_bf.pdf, Juni 2014.

[25] Kraftfahrtbundesamt, “Fahrzeugzulassungen (FZ), Bestand an Kraftfahrzeugen nach Umwelt-Merkmalen,” Flensburg, URL: http://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2015/fz13_2015_pdf.pdf?__blob=publicationFile&v=2, April 2015.

[26] P. Plötz, T. Gnann, M. Wietschel and S. Ullrich, “How to foster electric vehicle market penetration? - A model based assessment of policy measures and external factors,” European Council for an Energy-Efficient Economy -ECEEE-, Paris: eceee 2015 Summer Study, Paris, pp. 843-853.

[27] P. Plötz, T. Gnann and M. Wietschel, “Modelling market diffusion of electric vehicles with real world driving data. Part I: Model structure and validation,” Working Paper Sustainability and Innovation, No. S4/2014, URL: http://www.econstor.eu/handle/10419/96521.

[28] S.J. Tong, A. Same, M.A. Koostra and J.W. Park, “Off-grid photovoltaik vehicle charge using second life lithium batteries: An experimental and numerical investigation,” Applied Energy 104, pp. 740-750, 2013.

[29] U.K. Debnath, I. Ahmad and D. Habibi, “Quantifying economic benefits of second life batteriesof gridable vehicles in the smart grid,” Electircal Power and Energy Systems 63, pp. 577-587, 2014.

[30] N.N., “Erwartete Stückzahl an verfügbaren Batterien in 2nd Life Anwendungen in Europa“, URL: http://www.eol-is.de/sites/www.eol-is.de/files/u4/pictures/Marktentwicklung.png.

[31] B. Klör, D. Beverungen, S. Bräuer, F. Plenter and M. Monhof, “A Market for Trading Used Electric Vehicle Batteries – Theoretical Foundations and Information Systems,“ ECIS 2015 Completed Research Papers, Paper 105, ISBN 978-3-00-050284-2.