A MARKET FOR TRADING USED ELECTRIC VEHICLE BATTERIES – THEORETICAL FOUNDATIONS AND INFORMATION SYSTEMS

Complete Research

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Abstract

Various automotive companies have demonstrated that used electric vehicle batteries (EVBs), after having been removed from electric vehicles (EVs) due to insufficient capacity or power, can still be repurposed as energy storage for stationary applications. If predictions on the diffusion of EVs prove true, a large amount of used EVBs will be available for repurposing until the end of this decade. As yet, the fundamental economic properties of a market for used EVBs are unexplored. Additionally, the role of information systems as enablers for second life business models and tools for trading used EVBs has not been investigated. Inspired by seminal economic theories and based on reviewing the market for used automotive parts, we offer a first conceptualization of three forms such a market might take, along with their economic properties and stakeholders. We subject these market forms to a conceptual transaction cost analysis and an empirical inquiry based on semi-structured interviews. We find that a market for used EVBs will likely emerge as an intermediary-based market that is supported by automobile companies. Against this backdrop, decision support systems seem to be a more suitable class of information systems than electronic marketplaces to enable the trading of used EVBs.

Keywords: Electric Vehicle Battery (EVB), Lemon Market Theory, Principal Agent Problem, Transaction Cost Analysis, Decision Support System, Electronic Marketplace.

1 Introduction

The spread of the electric propulsion technology can be expected to fundamentally transform the automotive sector. This transformation enables consumers to utilize eco-friendly individual transportation and opens new business fields for innovative companies. In comparison to vehicles that are propelled by traditional combustion engines operating on gas, electric vehicles (EVs) run with electric motors that consume electric current. In order to store and provide the required energy, EVs contain special energy storage facilities, namely electric vehicle batteries (EVBs).

Today, lithium ion is considered to be the most appropriate cell chemistry for EVBs (Dinger et al., 2010). However, lithium ion batteries degrade over time due to calendar ageing and cycle ageing, both of which negatively impact the batteries' performance (Ebner et al., 2013; Sasaki et al., 2013). Automobile manufacturers expect an EVB's end of first life to occur after about five to eight years of usage or 100,000 kilometers of distance travelled (BMW AG, 2013; General Motors, 2013; Nissan Motor Co. Ltd., 2014). At that time, a replacement of the EVB is required to recover both the EVs' original driving range and acceleration. However, as a removed EVB still contains a remaining state of health (SOH) of approximately 80%, their repurposing and further use in various second life applications seems to be a reasonable strategy to generate additional revenues (Keeli and Sharma, 2012).

To overcome the high initial costs of EVs, researchers have started to explore options for decreasing the selling price of EVBs, which can account for up to 50% of the EVs' total price (Lih et al., 2012). Besides progress in the technological development of energy storage systems, the repurposing of batteries and their further use in less demanding second life applications is a promising option to generate additional revenues with used EVBs before their recycling and disposal. As yet, some proof of concept projects have been launched by leading industrial companies. Vattenfall and BMW are cooperating to repurpose used EVBs from the ActiveE or i3 as a flexible storage solution for energy generated from renewable sources or for stabilizing the energy grid (Vattenfall GmbH, 2013). In Hamburg, the used EVBs are used as a buffer energy storage facility to enable fast charging services for EVs. With used batteries from the Nissan LEAF, Nissan operates a commercial scale storage system in Osaka, Japan (EVWorld.com Inc., 2014). General Motors repurposes used EVBs from their plug-in hybrid and electric vehicles for a second life as a whole-house uninterruptible power supply (Howard, 2013).

With constantly growing sales figures of EVs, it seems likely that further business models will arise and a prospering market for reusing EVBs will emerge in the future (Ahmadi et al., 2014; Elkind, 2014). However, to this day, the economic properties of a market for used EVBs, including desirable market forms and the involved stakeholders, are still unexplored.

Seminal economic theories have introduced characteristics of markets for offering used goods. The noble-prize winning lemon market theory states that markets for used goods are impacted by high uncertainty due to an asymmetric distribution of information between seller and buyer (Akerlof, 1970). The hidden characteristics of a used good are one of the main drivers for asymmetric information that can lead to market failure and might even let the entire market disintegrate. EVBs are very complex goods that can be expected to feature significant hidden characteristics, resulting from a unique use history of each individual battery and high variance in the quality of different batteries of the same kind (Baumhöfer et al., 2014). Therefore, the identification of the 'best' scenario to repurpose an EVB requires in-depth knowledge on a battery. However, these data is unavailable for most actors, while specific and very expensive assets and competencies are required to reveal the characteristics of a used EVB, such that these characteristics might remain hidden. It is, therefore, reasonable to assume that a market for used EVBs is a lemon market, too.

The objective of this paper is to investigate the economic properties of a market for used EVBs. Based on seminal economic theory and drawing an analogy to the market for used car parts, we argue that three market forms need to be considered: (1) a *closed market* driven by an automotive or battery manufacturer, (2) an *intermediary-based market*, and (3) an *open market* (agora) in which buyers and sellers are directly dealing with each other. To identify the most suitable market form for trading used EVBs, we scrutinize both, the markets' properties and the market stakeholders' interdependencies. We triangulate this analysis by performing semi-structured interviews with key informants from battery companies, battery testing facilities, recycling specialists, and service providers. Based on these results, we reason which class of information systems needs to be put into place to enable a market for used EVBs. Thus, we answer the following research question: *What properties will a market for trading used EVBs have and what class of information systems will the market participants need?*

The remainder of the paper is structured as follows. In Section 2, the key economic properties of EVBs and seminal economic theories for trading used EVBs are reviewed. In Section 3, the research method is documented. In Section 4, the three proposed market forms are introduced. After matching the markets' characteristics with the properties of classes of information systems in Section 5, the market forms are analyzed against the backdrop of transaction cost theory and selected results obtained from the semi-structured interviews are presented in Section 6. Section 7 concludes the paper.

2 Theoretical Background

2.1 Technical Properties of EVBs and their Economic Implications

In comparison to a gas-operated vehicle, the initial high costs of an electric vehicle are due to the incorporated EVB (Hanna et al., 2012). In particular, EVB's costs mainly result from its elaborate construction process (Dinger et al., 2010) and the costly materials, such as lithium, cobalt, and nickel, the battery is composed of (Korthauer, 2013). For reducing the overall weight of EVs, most EVBs consist of lithium ion cell chemistries that are far superior to that of regular consumer batteries in terms of energy and power density (Han et al., 2014). Consequently, the repurposing and further use of used EVBs seem reasonable as long as the technical requirements of the second life applications can still be met and as long as the manufacturing of new batteries is significantly more expensive than the resources consumed while repurposing the battery (Neubauer et al., 2012).

Although different types of EVBs exist (e.g., full-electrics, plugin-hybrids, and hybrids) all batteries have a similar structure and typically consist of the battery pack, the battery management system (BMS), the thermo-system, and the battery case (Ellingsen et al., 2014; Klör et al., 2015; Schlick et al., 2011). The central component, the battery pack, is a modular device consisting of several combined modules, each of which again consists of several battery cells. The varying electric requirements of an appliance (e.g., voltage, current, and capacity) can be met by connecting the battery cells or modules in series or in parallel. Consequently, an EVB does not have to be interpreted as a single tradable good, but can also be disassembled into its components, which can then be repurposed and offered as independent energy storage solutions on the market.

One of the central influencing factors for determining the further use of an EVB is its degradation caused by aging. Lithium ion batteries do not only age by use (cycle life), but also by time (calendar life) (Barré et al., 2013). Various factors are known to influence the aging behavior, such as ambient temperatures, discharging current rate, charging rate (e.g., fast charging), depth of discharge, and time intervals between full charge cycles (Barré et al., 2013; Han et al., 2014; Rezvanizaniani et al., 2014). The degradation and aging behavior have strong consequences for a battery. On the one hand, using a degraded battery, e.g. in a mobile application, will lead to a lowered range and less acceleration force of the vehicle (Barré et al., 2014). On the other hand, an EVB's usage history also influences the resilience of the battery in its second application.

For identifying a suitable second life application after a battery's automotive life, specific equipment and test procedures are required (Ahmadi et al., 2014; Burke, 2009). In general, there are two ways to assess an EVB's core properties: First, usage data from the BMS or the EV's board computer can be downloaded via mostly non-standardized interfaces and employed as a foundation for estimating the suitability for and aging behavior during a second life application. However, most of the data are encrypted and can only be decrypted by the automobile company. Second, manual testing procedures require a special high-voltage training as well as a specific equipment and are not feasible to treat high numbers of batteries due to long runtimes. Thus, the number of actors on the market for used EVBs that are capable of reliably assessing an EVB's quality and enabling its reuse is very limited, as yet.

Moreover, the operating conditions for lithium ion batteries are limited and the chemical reactivity of a cell's materials in case of an improper use is high (Lu et al., 2013). Thus, lithium ion batteries are rated as dangerous goods, which poses strict restriction on the trading of the batteries in terms of transportation and importing (e.g., defined by European law (ADR, 2011)). For ensuring a proper and hazard-free operation in a second life application the battery has always to be adapted to the specific technical and environmental requirements of a further use application. A possible consequence is the establishment of companies that are competent for dealing with, e.g., the complex transportation (Klör et al., 2014) and initial operation of a battery and focus on the offering of these services on the market.

Even in the light of these difficulties, reputable estimations indicate the great ecologic and economic potential of applying used EVBs to second life applications (Hoyer et al., 2011). Consequently, the establishment of according markets can be seen as a worthwhile endeavor. With respect to the aforementioned restrictions of treating used EVBs, bringing together suppliers and customers of used EVBs is challenging. In the spirit of sophisticated closed-loop supply chain networks, suitable organizational and technical infrastructures are required to support the involved stakeholders in trading used EVBs.

However, only little research has been performed in this regard yet. As a starting point for identifying related work on an economic perspective on trading used EVBs, we conducted a literature review[1]. Searching the databases Scopus (total hits: 1; relevant hits: 0), AISEL (6; 0), and Springerlink (38; 0) revealed no relevant hits. The retrieved articles solely deal with topics such as residential load levelling (Rogers, 2012) and a business model (Kahlen et al., 2014) as well as technologies (Droste-Franke et al., 2012) for grid balancing. Consequently, our research starts almost on a green field.

2.2 Review of Economic Theories

Due to the high uncertainty impacting the trade of used EVBs, we consider three seminal economic theories to investigate the functions and implications of a market for used EVBs: The lemon market theory (LMT), the principal-agent problem (PAP), and transaction cost analysis (TCA). All three theories deal with information problems in the subfield of new institutional economics (Bardhan, 1989). Whereas the neoclassical economic models assume complete information on markets, the new institutional economic theory builds upon the premise of bounded rationality (Simon, 1985) and argues that the rationality of individuals in terms of decision-making is inherently limited, e.g., by incomplete information. Information asymmetry, a central assumption made in new institutional economic theory, can be described as the inability to accurately evaluate quality prior to purchasing or contracting (Mishra et al., 1998). Hidden characteristics, as one type of information asymmetry, describe a situation in which a customer is not able to identify the product as a high-quality or low-quality product. The theories' core statements and impact on trading used EVBs are summarized in Table 1.

Theory	Core properties	Consequences for a market for trading used EVBs
LMT	Asymmetric information, as a consequence of hidden characteristics, lead to adverse selection that subsequently dissolves the market.	Remove the uncertainty that is caused by missing knowledge about the battery's condition, by revealing information on the EVB and identifying suitable scenarios for repurposing.
PAP	Asymmetric information and utility maximization efforts of both principals and agents lead to market failure.	Information asymmetry can be reduced by screening an EVB's quality (seller) and signaling the scenario's needs to the provider (buyer).
TCA	Depending on the particular characteristics of a transaction, minimizing transaction costs can be achieved by choosing a proper governance structure.	A make-or-buy decision has to be made to identify the best governance structure for trading used EVB, in terms of lowering the transaction costs caused by the exchange.

Table 1. Core properties of a market for used EVBs, viewed from seminal economic theories

Lemon market theory

The lemon market theory was originally developed for describing the market behavior of trading used cars (Akerlof, 1970). The theory explains how information asymmetries, mainly established by the uncertainty about the actual quality of used cars as a result of their hidden characteristics, lead to ad-

[1] ("electric vehicle battery" AND ("trade" OR "trading") AND "market"), conducted on November 5th, 2014

verse selection and consequently to market failure. When purchasing a used car, a customer is usually unable to distinguish between high-quality cars (so-called 'cherries') and low-quality cars (so-called 'lemons'), since only little or even no information about the actual quality of the car is available. Thus, the customer accounts for the risk of buying a low-quality car by choosing a lower-than-average price. This customer's lowered willingness-to-pay results in the realization of a lower price than what would actually be adequate for a high-quality car. Since it is not desirable to sell high-quality cars under value, this process of adverse selection consequently drives high-quality cars out of the market. The seller can reduce the problem of asymmetric information by selling brand-named goods, licensing practices, or by providing guarantees or other services (Akerlof, 1970).

Principal-agent problem

The principal-agent problem arises due to information asymmetry and utility maximization efforts of both principals and agents. Adverse selection in the context of principal-agent theory is formed as follows. The principal assigns a service or a task to be carried out by the agent. To make sure the agent acts in the interest of the principal, the principal has to control the agent and thus reduce the existing information advantage of the agent. Concerning hidden characteristics, the principal will try to make the agent partially reveal the hidden characteristics through screening him (Spremann, 1987). This screening may result in self-selection, where the principal offers several different contracts and each agent will pick the contract that suits him best, thereby revealing information about himself to the principal (Spremann, 1987). The agent can lower the existing information asymmetry by providing signals to the principal that reveal hidden information, e.g., on product quality (Spremann, 1987). The costs for monitoring and signaling are called agency costs (Jensen and Meckling, 1976).

Transaction cost analysis

The transaction cost analysis, influenced by Coase (1937) and Commons (1931), was mainly established by Williamson (1975, 1979, 1981). TCA evaluates a transaction's present governance structure to find the transaction's most cost efficient governance structure (Williamson, 1975, 1979, 1981). As governance structures for a transaction, Williamson proposes markets, hierarchies, and hybrid contractual agreements (Williamson, 1979). In each economic exchange, asymmetric information, bounded rationality, and opportunism cause transaction costs (Williamson, 1981). Transaction costs are the "costs of planning, adapting, and monitoring the task completion" (Williamson, 1981, p. 552 et seq.). The magnitude of transaction costs is determined by the dimensions *asset specificity*, *frequency*, and *uncertainty* (Williamson, 1979).

First, asset specificity, conceptualized as site specificity, physical asset specificity, and human asset specificity arises from a fixed investment that is specialized on a particular transaction and cannot be used for any other purpose than the original transaction without a loss of value (Williamson, 1979, 1981). High asset specificity represents a risk for the investor, since an asset with a specific use can only be used for a certain type of transaction. Thus, the investor depends on the supplier if the transaction is about to be conducted on a market. Since new institutional economic theory assumes opportunistic behavior for every individual, the supplier will try to exploit the investors' dependency for his own benefit (John and Weitz, 1988). In turn, the investor will try to minimize the risk of opportunistic behavior through complex contracts, which in return increase transaction costs (Williamson, 1981).

Second, the frequency (one time, occasional, and recurrent) in which transactions recur (Williamson, 1979) is important. A non-specific transaction with high or low frequency should be implemented as market governance (Williamson, 1979). We contend that repurposing used EVBs is occasional today, but will be a recurrent task after the market has evolved further.

Third, the parties involved in a transaction will likely try to reduce uncertainty through complex contracting, which in turn increases transaction costs. A transaction that is subject to high uncertainty is, therefore, most efficiently governed by one vertically integrated party alone (Walker and Weber, 1984). There are two major sources of uncertainty: behavioral uncertainty arises from information asymmetries and opportunism between the parties conducting a transaction (Williamson, 1985), whereas environmental uncertainty can be described as "unanticipated changes in circumstances surrounding an exchange" (Noordewier et al., 1990, p. 82). The magnitude of the transaction costs determines the most efficient governance structure for a transaction and basically leads to a make-or-buy decision (Walker and Weber, 1984).

3 Research Method

The two core research objectives of this paper are to identify the economic properties of a market on which used EVBs are traded and to identify which classes of information systems need to be designed and implemented to support the trading of EVBs on these markets.

To reach these objectives, we organize our research process in three consecutive steps. First, we conducted a comprehensive literature review to identify related work. Second, we performed a conceptual analysis, applying seminal economic theories as a device of mind (Gearing, 2009) to reason about the theoretical properties of such a market. Conceptual research is "a non-empirical research method" (Mora et al., 2008, p. 113) for developing theory, based on reflecting on existing theoretical concepts. Inspired by literature on market engineering (Weinhardt et al., 2003), an analysis of the properties, stakeholders, and implementations of a market for trading used EVBs was conducted. Since on a high level of abstraction EVBs can be viewed as automobile parts, we identified market forms that are used to trade automobile spare parts. These market forms were subjected to a conceptual transaction cost analysis to identify which of the organizational forms will likely minimizes transaction costs.

Third, to triangulate this conceptual analysis with qualitative empirical field data, we performed a series of semi-structured interviews (inspired by Yin (2013, pp. 110–113)) with eight key informants. The informants deal with manufacturing, analyzing, transporting, using, or recycling complex battery systems in their day-to-day work (Table 2). Therefore, even if the properties of a non-existing market cannot be identified empirically with complete certainty, we can reasonably assume that the experts have a strong grasp of the technical properties of EVBs and the actors that might be active once such a market will be emerging. All interviewees received our interview guidelines prior to the interviews, such that they could prepare their answers. The interviews were performed on the phone and were documented with voice recordings (approved by the interviewees), leading to 189 minutes of raw audio data. After having conducted the interviews, saturation was reached since a rather uniform and consistent picture of a market to trade used EVBs emerged.

Organization	Role of key informant
Service provider	Managing director; Engineer
Association for technical inspection	Managing director
Battery manufacturing company	Managing director; Battery specialist
Consultancy for recycling / reverse logistics	Consultants (2)
Battery recycling company	Process engineer

Table 2. Overview of key informants of the qualitative interviews

4 Properties of a Market for Trading Used EVBs

4.1 Market Forms and Involved Stakeholders

To identify suitable market forms for trading used EVBs, we reviewed the existing market for trading used automotive parts, which comprises customer-to-customer, business-to-customer, and customer-to-business-to-customer relationships (Fichter, 2003; Lucas, 2000, 2001). Closed markets are used by original equipment manufacturers (OEMs) such as Ford Motor Company (2014) and Toyota (Sonic Automotive Inc., 2014). Operating as intermediaries, platforms such as ASM Auto Recycling Ltd. (2014) and Automotix LLC. (2014) can be used to buy and sell used automotive parts in customer/business-to-business-to-customer settings. In the spirit of open markets, business/customer-to-customer relationships can be observed on platforms such as eBay Inc. (2014), Alibaba (2014) and Gumtree (2014). Hence, to organize the trading of used EVBs, the three market forms (1) *closed market*, (2) *intermediary-based market*, and (3) *open market* have been adapted and are outlined as follows.

First, in a closed market, an EVB's lifecycle is entirely covered by the OEMs, including the automotive or battery manufacturers. In accordance with the EVB's first life, the automotive manufacturer executes rental, lease, or value-added services to make sure that the batteries are only passed back to the distributing company itself (Östlin et al., 2008). In addition to this ownership-based relationship, service contracts, mandatory deposits, and buy-back programs are methods to establish a closed-loop supply chain (Östlin et al., 2008). To meet the technical requirements of the second life scenarios and add value-added services, the automobile company might cooperate with battery manufacturers to reconfigure the battery to fit its new application scenario (Figure 1).

Figure 1. Closed market of OEMs selling used EVBs to customers

Second, based on the requests of second life customers, an intermediary might collect used EVBs from car owners, automobile companies, and battery manufacturing companies to offer them for use in second life applications (Figure 2). In this scenario, the intermediary configures the offer by eventually modifying the EVB and adding value-added services to meet the requirements of a second life scenario with regards to a repurposed energy storage solution.

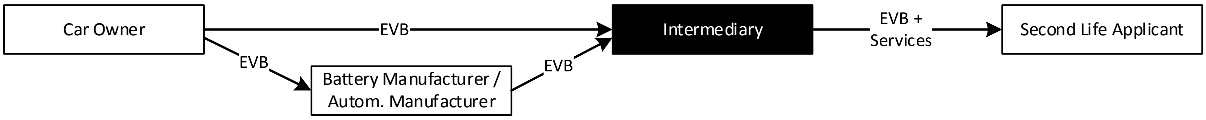

Figure 2. Intermediary-based market for scraping together EVB suppliers and customers

Third, a marketplace operator might run an open market to bring together supply and demand of used EVBs on an online marketplace. Value-added services for modifying, transporting, installing, maintaining, and replacing the used EVBs are also traded on the market and might be offered by independent service providers (Figure 3). Since the access to the marketplace is unrestricted, stakeholders from both business and private households establish the supply on the sell-side. The same applies for the buy-side as now everyone can freely demand for used EVBs by having access to the open market. As a central characteristic of perfect competition, the number of marketplaces is not limited to a single instance and may consequently result in a competition for the supply and demand of used EVBs.

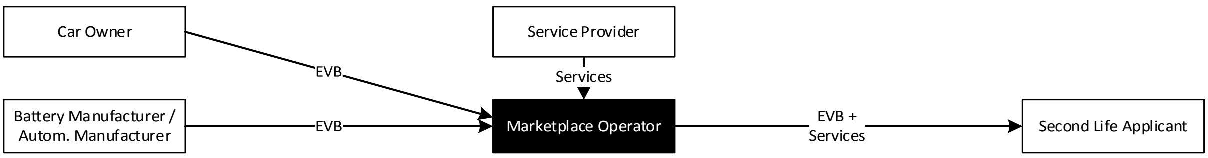

Figure 3. Open market for bringing together EVB suppliers and customers on a marketplace

4.2 Objectives, Competencies, and Interactions of the Stakeholders

In the following, we briefly introduce the stakeholders involved in the introduced market forms, including *EV owner*, *intermediary*, *OEM*, *marketplace operator*, *service provider*, and *second life applicant*. For conducting a systematic definition and description of the stakeholders, we apply the three concepts (1) *objective*, (2) *core competency*, and (3) *interactions*. First, objectives refer to the individual stakeholders' aims to be achieved on the market. Second, core competencies refer to a skill or a set of skills enabling a company to deliver certain customer benefits, such as providing access to a variety of markets and limiting imitation by competitors (Prahalad and Hamel, 1990). Third, interactions focus the core activities performed for and with other stakeholders.

Independently from the shape of a market, the supply of used EVBs is mainly established by the *EV owners*. Their basic aim is to minimize the total costs of ownership by generating additional revenues through selling their used EVBs. Since EV owners act privately on the market, there are no specific core competencies available. Except for the open market, EV owners are consequently not able to supply the batteries on their own due to the lack of knowledge about the battery's quality and applicability. For fulfilling these tasks, EV owners either hand back an EVB to the OEM in a closed and intermediary-based market or to an intermediary in the intermediary-based market if the batteries are acquired and not leased when purchasing an EV.

An *intermediary* is an optional stakeholder that is present in an intermediary-based market. There may be several stakeholders able to run a business with used EVBs, including battery recycling companies, associations for technical inspection, and public trusts as yet organized for, e.g., reprocessing consumer batteries (GRS Batterien, 2014). Since intermediaries need to have detailed knowledge on the structure and status of a used EVB, they require access to the encrypted battery data by permission of the automotive company and battery manufacturer. In combination with the intermediary's specialized knowledge on treating used EVBs, the business becomes beneficial due to capitalizing on economies of scale. Thus, intermediaries might trade EVBs from all automotive and battery manufacturers.

By definition, automotive and battery manufacturers are the *original equipment manufacturers* of an EVB. The primary objectives of OEMs are to defend, sustain, and extend the companies' market positions. With an increasing availability, customers might consider used EVBs as genuine substitutes of new batteries. By supplying remanufactured EVBs, the OEMs may establish a competitive advantage over competitors by vertical product differentiation (Ferrer and Swaminathan, 2006; Porter, 1980). Since legal regulations in many countries require OEMs to take back their EVBs they have put on the market, OEMs strive for supplying the used EVBs in all types of markets. In addition, if operating a closed market, OEMs are able to unfold their fundamental core competency, which is built on detailed knowledge on the battery's technical properties. This knowledge enables OEMs to assess an EVB's status, reconfigure it to fit the requirements of a second life scenario, and warrant its operability.

Only in open markets the appearance of a *marketplace operator* is required for merging the supply and demand of used EVBs. Since the marketplace operator's profit directly depends on both, the amount and frequency of transactions carried out on the marketplace, the operator's primary objective can be assumed to be facilitating a growing market for used EVBs. Since suppliers and customers interact freely, the marketplace operator has to provide the users with an online marketplace that is able to create feasible matches between supply and demand with respect to the stock of available EVBs. Furthermore, third party service providers may place their offers to get used EVBs working in second life applications. Hence, the online marketplace needs to recommend suitable services to customers.

Just like a marketplace operator, independent *service providers* act on open markets, only. The rationale behind this assumption is that the access to open markets is unrestricted, such that all companies might offer their services to customers. Since operating an EVB in a second life scenario requires services for, e.g., transport, assembly, and maintenance, customers might perceive these services as valuable. In the spirit of perfect competition, service providers act on markets for generating revenues, maximizing profit, and thus making attractive and competitive offers. Due to specialized knowledge about the services offered, service providers can determine the suitability of the requested services (up-selling) and may suggest additional actions (cross-selling) needed for second life applications.

On the buy-side of all market forms, the *second life applicant* defines requirements for an energy storage solution and thus constitutes the demand for used EVBs on the market. Due to the objectives of minimizing costs, risk, and, hence, maximizing utility, the technically less demanding second life applications request for used EVBs that fit these requirements. Thus, the second life applicants' core competency refers to defining their actual needs to put sellers of used EVBs in a position to remanufacture a valid solution. Additionally, for minimizing risk, second life applicants might request services provided by other stakeholders.

5 Classes of Information Systems for Trading Used EVBs

In the light of the expected properties of a market for used EVBs, information systems need to be designed to enable suppliers and customers to trade EVBs for mutual advantage. Against the backdrop of seminal theory in the information systems discipline, we identify decision support systems (DSSs) and electronic marketplaces as classes of information systems that can be used towards this end.

5.1 Decision Support Systems for Closed and Intermediary-Based Markets

While used EVBs will increasingly be available for second life applications within the next years, the decision problem of matching used EVBs to second life and vice versa seems to become a hard one. For dealing with both the problem of matching EVBs and scenarios and the present lack of information that are required for making technical judgments of an individual EVB, DSSs can be used.

DSSs are expert systems (Sen and Biswas, 1985) for improving decision quality by generating, assessing, and comparing feasible decision alternatives. Depending on the individual decision problem, different types of DSSs apply for solving the problem, such as data-driven, document-driven, or model-driven implementations (Alter, 2004; Power, 2000). Data-driven DSSs focus on retrieving information of large data sets, whereas document-driven DSSs focus on retrieving information of unstructured documents. Since model-driven DSSs mainly apply analytical and mathematical models (Power, 2000), for trading EVBs, this class of DSSs needs to be chosen to perform a sophisticated technical assessment, whereas economic decision models are required for supporting the decision process.

From an architectural point of view, DSSs contain three basic components (Le Blanc and Jelassi, 1989; Shim et al., 2002; Sprague Jr. and Carlson, 1982): (1) user interface, (2) model base management system (MBMS), and (3) database management system (DBMS). First, the decision-making process is facilitated by a graphical user interface for carrying out all necessary operations such as data acquisition, model building, model application, and data analysis. Second, the MBMS contains models that reconstruct the business context and, hence, the problem domain that requests for decision support. Third, the relevant data for feeding the decision models is extracted from internal and external data sources and loaded to the DBMS.

We argue that five models are required to support decision-makers in all phases of the decision process: an *assessment model* for determining an EVB's quality and applicability in specific second life applications; a *knowledge-based reconfiguration model* for both selecting EVBs that are appropriate to be reconfigured on a component level and for conducting the reconfiguration of eligible EVBs; a *matching model* for generating a consideration set of EVBs matching to second life applications and vice versa; a *decision model* for selecting feasible solutions manually and automatically (by linear programming); and a *service configuration model* for engineering individual solutions for customers. Moreover, depending on an EVB's type and condition, several further models for valuation are necessary, e.g., to calculate varying costs for battery transportation, recycling, and testing.

In order to supply the (decision) models with appropriate data, several data sources have to be included. In particular, as the central object of cognition, master data and transaction data of EVBs need to be included to determine the structure, use history, and status of an EVB. In their central position on the market, both OEMs and intermediaries obtain EVB data from the BMS directly. Furthermore, the integration of scenario data, service data, commodity prices, weather data, etc. is crucial.

5.2 Electronic Marketplace and Interactive Decision Aids for Open Markets

An open market for used EVBs can be realized as an electronic marketplace, on which different bidders and clients trade used EVBs without the involvement of other stakeholders. In general, an electronic marketplace is an online platform that brings together technically experienced and technically unexperienced sellers and buyers of goods as well as service providers. It is administered by a marketplace operator who might either be an independent organization or a consortium (Bakos, 1991). Typically, electronic marketplaces are favored over traditional marketplaces for several reasons, including reduced transaction costs and an increased market penetration (Malone et al., 1987).

Due to the complexity of EVBs and the high amount of data required for an informed decision concerning the potential repurposing and second life application of an EVB, the crux in an electronic marketplace for EVBs are the technical instruments supporting the selling and buying side interactively during the placement of an offering and the purchase of a properly configured solution. Due to the classification of an EVB as a dangerous good, sellers and buyers have to be informed about the requirement to consume value-added services that are enforced by law, such as transportation, initial operation and maintenance. Consequently, the online marketplace has to provide interfaces that allow service providers either to directly offer their services or through the marketplace operator (similar to the selection of a predefined logistic service at the end of a purchase in an online shop).

On the sell-side, users have to be supported in signaling the quality and status of the battery. Similar to existing marketplaces for used car parts, the operator of a marketplace for used EVBs is responsible for designing data structures and data samples that allow the sellers to identify and select EVBs, e.g., by selecting the production year of the original vehicle, the make, and the model. By providing simple means for specifying qualitative and quantitative data about the battery (e.g., damaged or undamaged, years since inception, mileage, region of usage) even a non-technical person is likely able to provide relevant data for a first classification of an EVB.

On the buy-side, potential customers have to be supported to find a suitable battery and value-added services for their particular second life scenario. Therefore, the users must be able to specify the properties of the required energy storage solution. Based on the provided requirements and battery data, interactive online decision aids (IODAs) can be utilized. IODAs are a class of decision support systems that are used for supporting purchase decisions in electronic markets (Häubl and Trifts, 2000). Following Wang et al., three different types of IODAs (comparison shopping agents, search engines, and recommender systems) can be distinguished (Wang et al., 2011). While comparison shopping agents aim to identify the best price for a product, search engines are a rather universal class of tools that may find products based on keywords provided by the customer (Wang et al., 2011). Based on the customer's interests or preferences, recommender systems support users facing preferential choice problems, like the problem of matching used EVBs and second life applications. One important component of recommender systems is the decision strategy (Wang and Benbasat, 2009), which describes how products are selected based on a customer's preferences. For preferential choice problems, the two most common decision strategies are the elimination and additive-compensatory models (Wang and Benbasat, 2009). The elimination strategy is based on thresholds for certain attributes of the product. Alternatives containing attributes that do not meet the threshold are excluded from the consideration set. In the additive-compensatory model the customer assigns weights to characteristics of the product and the IODA computes a score based on this weights resulting in a list of alternatives (Wang and Benbasat, 2009).

To enable an open market for trading used EVBs, a combination of both strategies is required. Therefore, technically unsuitable batteries can be eliminated in a first step. The remaining set of EVBs would be rated based on their attributes and the weighted properties of the second life application. Value-added services are recommended based on the characteristics of the battery, the scenario, and former transactions of similar combinations.

6 Transaction Cost Analysis of Market Forms for Used EVBs

Subsequently, we analyze which of the three presented market forms is likely to emerge for trading used EVBs. The analysis has two stages. First, a conceptual transaction cost analysis (TCA) is performed for repurposing used EVBs, based on the three characteristics (1) *asset specificity*, (2) *frequency*, and (3) *uncertainty*. This is done to determine the most suitable governance structure (market, network, or hierarchy) from a theoretical point of view. Second, semi-structured interviews with eight key informants were conducted. The results of both stages are reported subsequently.

After an EVB has reached its end of first life, it has to be removed from the car and its status needs to be analyzed. Handling EVBs requires a special training for the work with high-voltage energy storage systems. Although the number of EVs is growing, only few workshops seem to have hired employees that are skilled for these tasks. In addition to the general training, our informants confirmed that for the removal, replacement, and disassembly of EVBs even car brand-specific trainings are required and offered by the OEMs (human asset specificity). This is because battery systems have not been standardized, yet. The informants stated that, in some cases, even OEM-specific equipment is required.

For the next step, the assessment of the battery's performance and quality, two options are available. On the one hand, the battery data can be readout from the BMS, typically via CAN bus, a communication standard for microcontrollers and devices within vehicles. However, as emphasized by the interviewed experts, not only are the car manufacturers using individual designs of the CAN bus' hardware implementation (pinout), but the data are often encrypted. Consequently, only workshops and service operators that are equipped by the OEMs with suitable devices are able to perform a readout from the BMS and decrypt the data. As one interviewee notes:

> *"At the current point of time, the required equipment and tooling is highly proprietary. The reason for this is that OEMs will always try to protect their products, by locking the access for third parties or at least make it difficult." (Managing Director of Service Provider)*

On the other hand, especially if a readout from the BMS is not possible, a comprehensive manual electric assessment of the EVB's performance is required. For this purpose, costly test benches for handling high-voltage equipment and monitoring, the charging and discharging of the batteries, and their central parameters are required (physical asset specificity). The handling of the test benches equipment requires an electrical engineer with a specific training (human asset specificity). Although these test-benches can be used manufacturer-independently (after setting each battery's individual voltage thresholds and current), a bench can only process one EVB at a time. In combination with the requirement for performing several charging and discharging cycles before gaining a reliable assessment of the battery and acquisition costs of more than 150.000 euros per test bench (as confirmed by an association for technical inspection), the hurdles for manual testing of EVBs are considerable:

> *"If he [the OEM] restricts the access to the BMS […] it will be very costly to measure all those values, that means that I really have to do several performance cycles for determining the internal resistance, I have to perform a capacity check, and all of this has to be done individually for each battery, because I have to set the voltage threshold and I have to determine the current. For this purpose I need the information from the manufacturer about what is acceptable for the battery." (Managing Director of Association for Technical Inspection)*

Moreover, for repurposing the batteries, further prerequisites are to be met. First, a disassembly and reassembly of the battery system requires an electrical engineer with a training for high-voltage energy storage systems. The components of the battery system have to be adapted to meet the performance requirements of the second life application as well as the environmental surroundings of the place of installation. Since most OEMs build upon battery cells and modules that have been developed for the usage in a specific vehicle, varying dimensioning, performance characteristics, and operating conditions are faced during repurposing. In combination with the highly scattered aging behavior of the same types of cells employed in different vehicles, this leads to a very limited interchangeability of cells and modules from different battery packs and especially from different OEMs. Consequently, without a further standardization of the components and empirical data from second life applications, every repurposing forms a job production with small chances of realizing economies of scale.

Finally, our interviewees depict that these transactions are linked with high uncertainty and impede required investments for establishing repurposing-based business models. First of all, parametrical uncertainty is, e.g., caused by the uncertainty of the further diffusion of EVs, the development of the production costs for EVBs in comparison to the costs for the repurposing, the suitability of the batteries for and their performance in the second life applications, and a lack of clarity concerning the legal responsibilities in the context of the further use. As one participant puts it:

> *"I think that there are only few companies that are able to actually assess the whole thing with a high reliability and if they are capable of doing so, it causes high costs. That is mainly due to the lack of experience and because you do not really know, which information [about the EVB] are really relevant for determining the second life." (Consultant for Recycling and Reverse Logistics)*

Additionally, behavioral uncertainty is caused by automobile and battery OEMs' philosophy. Following the insights from our interviews, automobile OEMs are typically not interested in lowering the entrance barriers for unlicensed workshops and shy at the comparison of how well a vehicle deals with a battery during its automobile use. Consequently, the OEM will likely find additional technical-induced barriers to restrict the data readout and handling of batteries, if required:

> *"So when he [the automobile OEM] says: 'I'm not interested in an intermediary dealing with my batteries.' Then he can decide to stop the process [repurposing] of his own accord, by just not offering required information and then, I think, the repurposing will be so expensive that it does not pay off." (Managing Director of Association for Technical Inspection)*

Additionally, battery manufacturers might not be interested in a second life of their products at all, if this would cannibalize the market for brand-new energy storage systems. In contrast, a longer lifecycle of used batteries restricts the chances of a battery OEM to conquer these markets with new batteries:

> *"Of course, he [the battery manufacturer] rather wants to sell new stationary energy storage solutions. Consequently, he says: 'I don't care about the residual value. I just want to sell as many new products as possible. Thus, all used batteries should be directly recycled.'" (Managing Director of Association for Technical Inspection)*

In conclusion, the analysis has revealed that all three transactions are currently exposed to high asset specificity, especially shaped by required, partly even OEM-specific, qualifications for the handling of the batteries (human asset specificity) and the equipment for the battery assessment (physical asset specificity). Uncertainty is high, both in terms of parametrical and behavioral uncertainty, resulting in barriers for third parties to invest into specific equipment. Non-standardized characteristics and a small amount of available EVBs cause a low frequency and undermine any attempts for realizing economies of scale. For accordingly characterized transactions, the TCA recommends a hierarchical institutional setting as it would minimize transaction costs compared to a market or network governance structure. Especially due to the high asset specificity that burdens the removal and assessment of EVBs, at least from a TCA point of view, these transactions should be conducted within the hierarchy of a company.

Although they support the listed EVB properties and the factors influencing the complexity of the transactions, when directly asked about the likelihood of the three market forms, most interviewees state that an intermediary-based market and not a closed market is the most promising market form for repurposing batteries in the next couple of years:

> *"I think this scenario [closed market] is rather unrealistic. Tenor of the OEM: They are content if they get shot of their battery systems and their responsibility." (Process Engineer of Battery Recycling Company)*

As depicted by one interviewee, the European law currently rather enforces a closed market due to the strict regulations of the Waste Electrical and Electronic Equipment Directive (Directive 2012/19/EU, 2012) and the Battery Directive (Directive 2006/66/EC, 2006) that obligate the manufacturers or vendors to take-back, reuse, and recycle their products. Nevertheless, it is likely that the OEM will outsource their burden of repurposing and accepting returns.

> *"We already observe the trend that the OEMs are outsourcing the battery assessment towards third parties. Consequently, the number of similar service provides will further increase." (Battery Specialist at Battery Manufacturing Company)*

> *"Of course the automobile manufacturer might search someone, who relieves him of the tasks. […] I think that this market [the intermediary-based market] might prevail, where the automobile manufacturer says: 'I will look for a partner, who buys the batteries from me because I do not want to get in contact with all those end users [of second life applications].'" (Managing Director of Association for Technical Inspection)*

> *"I think that this is a very realistic scenario. In contrast to the closed market, I imagine that the automobile or battery OEM says: 'Man! Here is the intermediary and we provide him with all of our returned used batteries and he should use his competencies to decide about the further use, be it the recycling or a second life application.'" (Consultant for Recycling and Reverse Logistics)*

7 Conclusion and Outlook

The purpose of this paper was to identify and discuss core properties of a market for trading used electric vehicle batteries. Based on drawing an analogy to the existing market for trading spare parts for automobiles, we identified the main stakeholders participating on a market for used EVBs, as well as proposed three forms in which such a market might emerge in the next years. A conceptual transaction cost analysis of the three scenarios revealed that from the point of view of seminal economic theory, the market for used EVBs will likely be a closed one. However, an empirical study in which we conducted a series of semi-structured interviews with eight key informants revealed that the experts expect an intermediary-based market to emerge that is supported by the automobile industry. In this respect, the interviewees have merged characteristics of both 'pure' market forms into a new scenario that might be suitable to account for the core competencies and strategies of the involved stakeholders, without conflicting with our theoretical results.

Apparently, removing the inherent uncertainty from markets for used EVBs is the most crucial issue in order to run this business successfully. This claim especially holds true with regards to the buy-side of a business operating in closed or intermediary-based market forms that are likely to be adopted for trading used EVBs in a short- and mid-term perspective. The reason is the lack of knowledge about an EVB's usage history (Monhof et al., 2015), which in turn is due to both data encryption and insufficient data recording strategies of the currently available BMSs. Furthermore, it can be expected that the OEMs strive to preserve the status quo with respect to protecting their investments. Due to the incomplete and asymmetric information, the market for used EVBs might prove to be a lemon market, unless countermeasures are put into place by implementing appropriate information systems.

From the information systems discipline's point of view, these results mean that IT artifacts that enable trading used EVBs will likely have to be implemented rather as DSSs than as electronic markets. Subsequent research can use the results developed in this paper as justificatory knowledge for the design of IT artifacts and IS design theories (Gregor and Jones, 2007).

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