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Transactions for trading used electric vehicle batteries: theoretical underpinning and information systems design principles

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Abstract Proof-of-concept projects have demonstrated that used electric vehicle batteries (EVBs), after their removal from electric vehicles due to insufficient performance, can be repurposed for less demanding applications. It is expected that numerous batteries will be available for repurposing in the 2020s. However, the information asymmetries and transaction costs of trading used EVBs have remained unexplored, as have principles that guide the design of information systems that support the trade. Based on existing literature and in-depth interviews with battery experts, we conceptualize two key transactions for trading used EVBs. We then identify potential information asymmetries and transaction costs based on new institutional economic theory and propose five design principles that information

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systems should implement to address these information asymmetries and transaction costs. Subsequent research can build on our results to further frame the economic properties of trading used EVBs and to design information systems in line with new institutional economic theory.

Keywords EVB · Repurposing · Second life · Second use · New institutional economics · Design science

1 Introduction

The diffusion of electric propulsion technology can be expected to transform the automotive sector fundamentally, enabling eco-friendly transportation and new business opportunities for companies. Electric vehicles (EVs) consume electric current that is stored in and provided by electric vehicle batteries (EVBs). Unfortunately, lithium-ion chemistry-based EVBs degrade over use and time due to cycle aging and calendar aging, both of which negatively impact the batteries' performance (Ebner et al. 2013). Automotive manufacturers expect an EVB's end of first life to occur after about 6–8 years of operation, or at least 100,000 miles, respectively, 160,000 km of distance traveled (e.g., BMW AG 2016; Nissan North America Inc. 2016). Then, replacing an EVB allows recovering the EV's original driving range, acceleration, and charging speed. However, as most removed EVBs still have a usable capacity of approximately 70% to 80%, their repurposing and further use in second life applications might turn out as a reasonable strategy for generating additional revenues (Neubauer et al. 2015; Ahmadi et al. 2017). These revenues can help to offset the high initial costs of EVs (Elkind 2014), for up to 25% of which the EVB is currently responsible (Nykqvist and Nilsson 2015).

As steadily growing sales figures of EVs will result in an increasing number of used EVBs (International Energy Agency 2018), trading used EVBs will soon become a worthwhile business. While the economic foundations are still mostly unexplored, we argue that new institutional economic theory is a valuable lens to reason about the information asymmetries and transaction costs inherent in transactions for trading used EVBs. Transaction cost theory examines the economic costs that occur during a transaction and allows to compare different governance structures to minimize transaction costs (Williamson 1975). Principal-agent theory suggests that conflicting interests and asymmetric information might inhibit transactions carried out by agents on behalf of principals (Jensen and Meckling 1976). The noble prize winner George Akerlof (1970) demonstrated how uncertainty on the quality of used goods, and thus, again, asymmetric information between sellers and buyers might drive high-quality goods out of a market and can even lead to market collapse.

Understanding the economic properties of transactions for trading used EVBs is inseparably intertwined with designing and implementing information systems that enable these transactions. Design science research (e.g., Gregor and Hevner 2013) reminds us that the design of information systems needs to be based on design knowledge that is justified with theory. One means to convey such design

knowledge are design principles, i.e., justified statements or rules that guide or constrain design actions (e.g., Chandra et al. 2015; Seidel et al. 2018). Trading used EVBs will remain an unprofitable business as long as information systems that implement suitable design principles to foster information exchange among the involved stakeholders are missing.

In line with this observation, we set out to answer two research questions: What information asymmetries and transaction costs constitute the main transactions for trading used EVBs? What design principles must information systems implement to mitigate these information asymmetries and transaction costs?

The paper unfolds as follows. In Sect. 2, the fundamental characteristics of used EVBs are explained, and central theories from new institutional economics are presented. In Sect. 3, the research method is documented and justified. In Sect. 4, two core transactions for trading used EVBs are conceptualized and detailed based on existing literature and in-depth interviews with industry experts. Furthermore, potential governance structures for implementing these transactions are proposed. In Sect. 5, principal-agent theory and transaction cost theory are used as lenses to identify potential information asymmetries and transaction costs of both transactions. Section 6 presents five information systems design principles that mitigate these challenges. Section 7 concludes the paper.

2 Related research

2.1 Characteristics of used EVBs

About a quarter of an EV's costs is determined by the vehicle's EVB, which requires expensive raw materials and an elaborate construction process (Nykqvist and Nilsson 2015). Although most EVBs build on lithium-ion chemistries that are superior to consumer batteries regarding energy and power density (Han et al. 2014), they also degrade over use (cycle aging) and time (calendar aging) (Barré et al. 2013). The degradation is highly individual and known to be influenced by factors such as the ambient temperature, the charging and discharging current rate (driving profile), and the depth of discharge (driving range between charges) (Barré et al. 2013; Han et al. 2014; Rezvanianiani et al. 2014). The two main effects of degradation are a reduced capacity (limiting the vehicle's range) and an increased internal resistance (limiting acceleration and charging speed) (Vetter et al. 2005). Most researchers assume that a degradation of the EVB's residual capacity to about 70–80% marks the end of the battery's automotive life (e.g., Viswanathan and Kintner-Meyer 2011; Neubauer et al. 2015). However, the EVB's remaining performance still allows using the battery in less demanding second life application scenarios. Due to legal obligations in the EU, automotive manufacturers are required to take back their degraded batteries (e.g., Directive 2000/53/EC 2000; Directive 2006/66/EC 2006). Considering the increasing EV sales (International Energy Agency 2018), estimated numbers of some hundred thousand EVBs that

leave the automotive use each year from the middle of the 2020s onward (Foster et al. 2014) emphasize the importance of finding a second life for these goods.

As a used good, an EVB forms a complex system that can be traded as a whole, it can be disassembled into its components to be traded individually, or it can be integrated into and sold as a bigger system. The battery's core component is the battery pack, consisting of several modules, each of which comprises battery cells (Klör et al. 2015a; Saw et al. 2016). Connecting the cells and modules in parallel or in series allows adapting the pack to varying electric requirements of appliances. Additional components such as the battery management system (BMS), the thermal management system, and the casing also need to be tailored to the particular application. However, identifying the battery's suitability for a particular second life application scenario demands information on the battery's condition and its usage history, which strongly influence the battery's expected performance and further degradation (Ahmadi et al. 2017; Rohr et al. 2017). Moreover, EVBs are classified as dangerous goods, which restrict their trading and processing and legally demand specific qualifications for their handling (UNECE 2016). To ensure a hazard-free operation, professional reprocessing, transport, maintenance and—with increasing sizes—monitoring during the EVB's second life is necessary (Bräuer 2016).

2.2 Selected theories from new institutional economics

New institutional economics (NIE) analyzes the effect of institutions (e.g., laws, corporate structures) on transactions between individuals (North 1986). The NIE perspective differs from neoclassical economics, as it does not accept the premise of the availability of full and relevant information, but rather accounts for information problems (Bardhan 1989) that result from bounded rationality (Simon 1985) and incomplete information. NIE consists of three branches, focusing economic, legal, and political perspectives to analyze institutions. Based on an economic perspective, we analyze the trade of used EVBs for information asymmetry and transaction costs as the main influencing factors by applying the transaction cost theory (TCT), the principal-agent theory (PAT), and the resulting lemon-market problem (LMP).

2.2.1 Transaction cost theory

TCT, mainly established by Williamson (1975), examines the costs that occur while performing an economic exchange as a transfer of property rights of goods or services. TCT assumes bounded rationality (individuals are limited in their rational behavior due to information asymmetries, uncertainty, and complexity) and opportunism (individuals try to maximize their utility regardless of other individuals' well-being), both of which cause transaction costs (Williamson 1981). The concept of transaction costs refers to Coase (1937), who noted that using the price mechanism on the market is not free of costs. Transaction costs can be distinguished between ex-ante and ex-post transaction costs, depending on whether they occur before or after the conclusion of a contract. Ex-ante transaction costs are all costs that help to enable the realization of a transaction, such as gathering the necessary information, planning, drafting, negotiating, and securing an

agreement (Williamson 1985). Ex-post transaction costs are the costs of monitoring and enforcing an agreement and, if necessary, adapting to subsequent changes (Williamson 1985).

The magnitude of transaction costs is determined by the asset specificity, frequency, and uncertainty of a transaction (Williamson 1979). Asset specificity, deemed the most critical dimension, refers to investments that are specialized on a particular transaction and cannot be used for any other than the original purpose without a loss of value (Williamson 1979, 1981). The investor thus enters the risk of being exploited by the opportunistic behavior of the transaction partner, which the investor will try to minimize through complex contracting that causes transaction costs (Williamson 1981).

By analyzing the dimensions of a transaction, transaction cost analysis determines the most efficient governance structure (market, hybrid contractual agreements, or hierarchy) for a transaction to take place (make-or-buy decision) (Williamson 1979, 1981), where the main difference between the governance structures is the underlying contract law (Williamson, 1991). Market governance describes a setting where buyer and seller meet and the transaction is conducted via a single purchase contract—the classical sale (Williamson 1979). It is the setting with the lowest transaction costs for nonspecific transactions, both for single and recurrent transactions (Williamson 1979). A vertically integrated, centralized organization within which the transaction is concluded (hierarchical governance) is recommended for transactions with high specificity (Williamson 1979, 1981). The hybrid governance modes can take various forms of two organizations cooperating like long-term contracting, reciprocal trading, regulation, or franchising (Williamson 1991). The applied neoclassical contract law is more flexible than in a hierarchy but stricter than in a market (Williamson 1991). Hybrid modes are a compromise between the extremes of market and hierarchy as they combine advantages of both governance forms. A transaction is efficient, if it has the lowest transaction costs and production costs, while a trade-off between transaction costs and production costs might exist (Williamson 1985).

2.2.2 *Principal-agent theory*

PAT (Jensen and Meckling 1976) refers to a delegation relationship between two actors, where one (the principal) contracts another (the agent) to act on his behalf. The agent has an information advantage, and as the primary interest is maximizing his utility, the agent's actions will not always comply with the principal's goals (Jensen and Meckling 1976). Therefore, the principal has to apply measures such as incentivizing or monitoring to make sure the agent acts in the principals' interest, or the agent signals a good intention to the principal (e.g., by offering contractual penalties). In line with theory on information problems (Mankiw 2014), three types of information asymmetry that lead to coordination and motivation problems are introduced and differentiated subsequently.

Hidden characteristics leading to adverse selection The principal is not able to adequately judge the quality of the agent ex-ante the conclusion of the contract due

to an information asymmetry resulting from incomplete information (hidden characteristics), which drives high-quality goods out of the market (adverse selection) and may lead to market failure (Akerlof 1970). This so-called lemon-market problem was first described by Akerlof (1970) on the market for used cars: When purchasing a used car, a customer is assumed to be unable to distinguish between high-quality cars (so-called “cherries”) and low-quality cars (so-called “lemons”), since 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. The lowered willingness-to-pay drives high-quality cars out of the market (adverse selection). Solutions to reduce this information asymmetry are for the agent to signal the product’s quality to the principal (signaling) (Spence 1973), e.g., by selling brand-name goods, licensing practices, or the provision of guarantees or other services (Akerlof 1970). The principal can screen possible agents for their quality (screening) (Spremann 1987). Self-selection mechanisms offer the agent a set of contracts with, e.g., different prices, where the agent partially reveals information to the principal by choosing the preferred option (Arrow 1986). Verification by independent authorities is also proposed to reduce information asymmetry (Keil 2005), although it would have to be counted as signaling or screening as soon as one of the contracting parties pays for the verification.

Hidden action/hidden information leading to moral hazard After the conclusion of the contract, the principal is not able to fully assess the actions, respectively, effort of the agent (hidden action) or to evaluate the quality, respectively, output of the agent’s actions (hidden information) (Arrow 1986). The opportunistic agent may exploit this situation, for instance, by reducing the effort below the level previously agreed upon (moral hazard). Solutions are monitoring and contractual agreements that either explicitly restrict specific actions by the agent or provide incentives to act in the principal’s interest (Keil 2005).

Hidden intention leading to hold-up Ex-ante, the principal does not know how the agent will act or what the agent’s real motives are (*hidden intention*), but can see the results after the conclusion of the contract (Picot and Wolff 1994). As a consequence of specific investments, the principal might depend on the defecting agent, who in turn might exploit the situation (hold-up) (Goldberg 1976; Alchian and Woodward 1987). Preventive measures are the alignment of interests via contractual agreements.

3 Research method

Following Gable’s (1994) call for mixed method studies in information systems research that has especially been renewed by Mingers (2001) and by Venkatesh et al. (2013) for quantitative–qualitative studies, we used a four-step mixed method approach bridging the paradigm distinction of behavioral science and design science (Hevner et al. 2004) to conceptualize, analyze, and support transactions for trading used EVBs. First, we analyzed literature to elicit the value network, role descriptions of participants, and technical details about repurposing

and further using EVBs. Based on this material, we identified two basic transactions that constitute trading used EVBs. Second, to empirically elicit the roles and actors trading used EVBs and to finally determine efficient governance structures for these transactions, we performed semi-structured interviews [in line with Yin (2013, pp. 110–113)] with 20 key informants, all of whom deal with manufacturing, analyzing, transporting, using, or recycling complex battery systems in their day-to-day work (Table 1). The informants were interviewed regarding enablers, disablers, and the likelihood of three different governance structures for trading used EVBs [also see Klör et al. (2015b)]. All informants received our interview guidelines before the interviews. The interviews were performed on the phone and were documented with voice recordings, leading to 355 min of raw audio data. Extracts from the interview transcripts are provided as supplementary material. Saturation was reached, since the last interviews did not yield any new information and a consistent picture of the properties of the two transactions emerged. Third, we performed a conceptual analysis (Mora et al. 2008, p. 113) using TCT and PAT as a device of mind (Gearing 2009), to identify information asymmetries and transaction costs inherent to the two transactions. For facilitating the trade of used EVBs—which has not yet emerged beyond first prototype projects—the use of information systems is inevitable. Therefore, fourth and finally, we designed five design principles—justified statements or rules that guide or constrain design actions (Chandra et al. 2015; Seidel et al. 2018)—for developing information systems that enable or support trading used EVBs. The design principles address economic challenges that were identified in our conceptual analysis and are, therefore, firmly rooted in transaction cost theory, principal-agent theory, and the lemon-market problem as justificatory knowledge (Gregor and Hevner 2013).

Table 1 Overview of key informants of the semi-structured interviews

Stakeholder	The position of key informant
Association for Technical Inspection (ATI)	1 × Managing director (MD)
Battery Manufacturing Company (BMC)	2 × Project manager (PM1), (PM2)
Battery Research Center (BRC)	4 × Battery researcher (BR1)–(BR4)
Consultancy for Battery Recycling (CBR)	1 × Managing director (MD); 1 × Process engineer (PE)
Consultancy for Reverse Logistics and Recycling (CRL)	2 × Consultant (CR1), (CR2)
Service Provider (SPR)	1 × Managing director (MD)
Consultancy for Energy Industries (CEI)	2 × Manager (M1), (M2); 4 × Consultant (CE1)–(CE4)
Research Center for Energy Economics (RCE)	2 × Researcher (R1), (R2)

4 Transactions for trading used EVBs

4.1 Review of key roles in value networks for repurposing used EVBs

Research on EVBs' second use mainly focuses on the repurposing of EVBs as stationary battery energy storage systems, and findings from experiments and prototypical installations document that some stationary second life application scenarios are feasible (e.g., Williams 2012; Gohla-Neudecker et al. 2015, 2017). Although current literature does not yet discuss inter-organizational challenges that go along with the repurposing and further use of EVBs, we argue that descriptions of supply chains and the market for regular battery energy storage systems (Bowler 2014; Bräuer et al. 2016) can be used as a role model for a first conceptualization of the trade of used EVBs. Building on Bowler's (2014) description of "the stationary storage value chain", six roles are crucial in a value network for trading used EVBs. Component suppliers provide hardware, such as the used battery system, the battery management systems, or power electronics such as inverters or fuses. These components are utilized by system integrators to engineer and assemble the repurposed energy storage system for a particular application. System suppliers account for selling, distributing, provisioning, and maintaining the battery system. System operators purchase battery systems from system suppliers, might own multiple battery systems from different suppliers or a single supplier, and provide these systems to end customers. End customers pay for the service offered and capture value-in-use from the battery systems' operation. Finally, a recycling company is responsible for the recovery of valuable materials such as cobalt, nickel, and lithium and the disposal of non-recoverable wastes (Swain 2017). Bowler (2014) additionally emphasizes that a single actor can adopt one or several roles, whereas any role is fulfilled by at least one actor.

The presented role concepts can be used to describe the value networks of existing prototypical second use projects. For instance, a consortium of Daimler AG, The Mobility House AG, GETEC and Remondis SE has built a 13 MWh battery storage system in the German town Lünen that consists of more than a thousand of used battery packs from the smart fortwo electric drive and is used for grid services (Daimler AG 2016). After the return of the used smart batteries by the EV owners, Mercedes-Benz Cars, a division of the Daimler AG, provided the used batteries (component supplier) that were repurposed by Deutsche ACCUmotive GmbH & CO. KG, respectively, Mercedes-Benz Energy, both 100% subsidiaries of the Daimler AG (system integrator). The Mobility House AG and GETEC were responsible for the realization of the battery system and are now operating the system and monetize its services in the energy market (system supplier and system operator). Transmission system operators act as end customers that profit from the battery system's operation. Remondis SE is responsible for the recycling (recycling company).

In another prototypical second use project, Renault S.A. cooperates with Connected Energy Ltd to develop modular battery storage systems named E-STOR that act as buffer storage for electric vehicle charging infrastructure and thus relieve

the public grid (Renault 2016). While Renault solely provides the used battery systems (component supplier), Connected Energy Ltd is responsible for the repurposing of the battery systems, their installation, and their operation on site (system integrator, system supplier, and system operator). Potential beneficiaries are, for instance, charging infrastructure operators, but also EV owners that use the charging infrastructure (end customers).

Finally, Nissan and Green Charge Networks (now mainly owned by Engie) are cooperating in North America to offer the first commercially available second life battery storage systems for companies that build on used Nissan Leaf EVBs. In this value network, Nissan acts as a component supplier for the battery components and delivers the used battery packs with a 10-year warranty on their usability (St. John 2015). Green Charge Networks are responsible for the repurposing of the battery systems. Moreover, the company concludes 10-year contracts with their customers based on a so-called “Power Efficiency Agreement” (Green Charge Networks 2016). As a part of this agreement, Green Charge Networks install the battery systems at commercial customers and operate and own the systems (system integrator, system supplier, and system operator). As payment, Green Charge Networks receive a share of the power bill savings that are achieved by their customers due to the battery energy storage systems’ potential to lower peak demand usage and thus reduces peak demand charges.

As announced in summer 2016, companies are also moving towards repurposing used EVBs for private end customers. For instance, Nissan is cooperating with the power management company Eaton to market residential battery energy storage systems labeled “xStorage Home” in UK, Norway, and Germany, which can be equipped with new battery components but also components from used EVBs (Nissan Europe 2016). This step confirms earlier studies on the economic potentials of residential second life applications, for instance, the usage of second life battery energy storage system (SLBESS) in private households to increase the self-consumption of residential photovoltaic installations (Heymans et al. 2014; Assunção et al. 2016).

To keep the conceptualization and analysis of potential settings for trading used EVBs manageable, we focused our research on a limited number of roles and built on the following four assumptions:

1. A single entity adopts the roles of system integrator and system supplier and is responsible for engineering, assembling, selling, installing, and servicing the repurposed energy storage system. We call this integrated role the second life manufacturer.
2. A single entity adopts the roles of the system operator and end customer. We call this integrated role the second life customer.
3. Only the supply of the used battery systems is analyzed, whereas further transactions with other component suppliers are not considered.
4. The recycling company and additional authorities, such as governments or testing authorities, are not considered.

Consequently, the resulting simplified value networks comprise the roles of the component supplier, second life manufacturer, and second life customer.

4.2 Analysis of the strategic objectives and core competencies of key actors

We conducted a series of semi-structured interviews with 20 key informants to elicit the strategic objectives and core competencies of component suppliers, second life manufacturers, and second life customers. While strategic objectives refer to the individual actor's aims to be achieved by trading used EVBs, core competencies refer to a set of skills that enable a company to deliver certain customer benefits, such as providing access to a variety of markets and limiting imitation attempts by competitors (Prahalad and Hamel 1990).

As depicted in the real-world cases above, automotive manufacturers (in the following denoted as automotive OEMs) act as component suppliers for used EVBs. It can be assumed that their primary strategic objective is to sustain and improve their position on the markets for electric vehicles. Offering customers a buy-down for their used EVBs and thus lowering an EV's total cost of ownership (Cready et al. 2003; Elkind 2014) may create buying incentives for EVs that improve the automotive OEM's market position (ATI:MD°#4).¹ Moreover, the currently still costly recycling of the battery components is further postponed and contrasted with potential earnings from repurposed EVBs (ATI:MD°#3).

At the end of an EVB's first (automotive) life, battery redemption takes place (Gohla-Neudecker et al. 2015; Bräuer 2016). European law poses the legal obligation for this take-back on the automotive OEMs, respectively, collaborating car dealers or workshops (e.g., Directive 2000/53/EC 2000; Directive 2006/66/EC 2006). To prevent non-authorized third parties from performing maintenance work on the battery systems or accessing the battery systems' usage and status data, automotive OEM's employ proprietary components that demand for OEM-specific equipment and that use encryption on battery-specific data streams and stored battery data (CBR:PE°#2; SPR:MD°#1,°#3, CEI:M1°#1, BRC:BR2°#1) (Ahmadi et al. 2014; Monhof et al. 2015; Neubauer et al. 2015). Moreover, strong legal and regulatory requirements that result from an EVB's hazard potential and its labeling as a dangerous good set high knowledge and equipment barriers for handling and transporting used EVBs (CRL:CR1°#1, ATI:MD°#5, BRC:BR2°#1), which especially prevents most EV owners from performing maintenance work or the battery exchange on their own.

However, after battery redemption, the informants agree that the repurposing and marketing of used EVBs on an industrial scale lies outside most automotive OEMs' scopes, respectively, core business areas (CEI:CE1°#1; BRC:BR1°#2; CRL:CR1°#2, BRC:BR2°#1). Instead, OEMs are likely interested in turning non-reusable battery systems into cash and leaving the second use business to authorized, closely cooperating, and specialized second life manufacturers (CEI:CE1°#1; CEI:M1°#2, BMC:PM1°#3). As the OEM basically owns all assets

¹ The identifiers that are included to the square brackets refer to an informant's company followed by the role of the informant. To uniquely identify the statements, the following syntax is applied: "(<company>:<key informant> #<number of statement>)" For instance (ATI:MD°#4) refers to statement #4 made by a managing director (MD) of the association for technical inspection (ATI). The entire list of statements, including identifiers, can be found in the supplementary material, to display the complete chain of evidence.

relevant for testing and repurposing the used EVB like the EVB itself as well as knowledge on its composition and usage, it is self-evident that the OEM will play a central role in the repurposing process and may even opt for performing the whole process itself (RCE:R1°#1, RCE:R2°#1 BMC:PM1°#1, BRC:BR3°#1, BRC:BR3°#2). This statement is supported by the fact that automotive OEMs have to adapt their current business models to shifts in the value chain of EV production (BRC:R1°#2).

Since the used EVB's condition allows for reasoning on the EV's treatment of the battery as well as the battery components' quality—which is knowledge OEMs must protect—close cooperation and trust between the OEMs and second life manufacturers are essential. A corresponding relationship also helps OEMs to ensure that the targeted second life application of the used EVB or associated events do not damage the OEMs' brand (ATI:MD°#3). Thus, although the OEMs place the responsibility for the repurposing and marketing of the used EVB and thus further downstream services such as the redemption of the used battery systems and their recycling as well as the subsequent product liability on the second life manufacturers (CEI: CE1°#1; CRL:CR2°#2), they will likely still demand a voice in the business activities of the second life manufacturers. Consequently, scenarios for trading used EVBs in which the repurposing and downstream operations are completely out of the automotive OEMs' control are currently impracticable.

The role of a second life manufacturer might be adopted by companies that are already part of the automotive value network such as associations for technical inspection or recycling companies, might be filled out by companies that have experience in the battery business such as manufacturers of regular battery energy storage systems (BESS) or suppliers of battery system components (see the Renault case described above), or new companies might be founded that solely specialize in the battery second use business. The latter has been, for instance, observed with the start-up Freewire Technologies, which offers repurposed battery systems as mobile chargers and mobile power generators (Seiple 2015). Depending on the companies' background and the particularly targeted battery second use business model, the second life manufacturers' strategic objectives and required core competencies might differ in detail. However, on a high level of abstraction, a second life manufacturer's business is to sell repurposed battery system and complementing services to second life customers. In this case, the battery system's ownership is transferred to the customer. Alternatively, also the offering of the battery system as a service in use-oriented and result-oriented business models is possible (Bräuer 2016; Bräuer et al. 2016). In these cases, the second life manufacturer generates earnings from monthly or yearly service fees (especially rent or leasing) or from the customers' payments for the energy throughput or the number of charging and discharging cycles (pay-per-use). A further possible manifestation is implemented by Green Charge Networks, where revenue is directly linked to the customers' benefits from the system's operation, such as a reduced electricity bill or an increased self-consumption of residential energy (Green Charge Networks 2016).

All these business models have in common that the second life manufacturer has to retrieve used EVBs from the automotive OEMs and has to repurpose the battery systems to varying degrees, i.e., disassemble the battery components, test their

functionality, and re-assemble the battery systems or add further complementing components to fulfill the requirements of a targeted second life application scenario (Ahmadi et al. 2014; Bowler 2014). Moreover, the second life manufacturer needs to have competencies in integrating the battery systems into existing infrastructure and in performing maintenance work (CEI:M2°#2). Consequently, a second life manufacturer interacts directly with both, the component suppliers and second life customers.

A tremendous proportion of the second life manufacturer's risk is due to the need to invest in equipment for and knowledge on testing a battery's status and properly disassembling, re-assembling, and configuring a repurposed battery system (including the BMS and additional communication hardware) (BMC:PM1°#1; CBR:PE #3; CEI:M1 #1; CEI:M2°#2; CRL:CR2 #1). Since manual tests for identifying a battery's quality and matching similar cells or modules are enormously time-consuming and require highly trained personnel, the economic feasibility of the repurposing mainly relies on the availability to assess a battery's condition and usage history to limit the manual testing (Cready et al. 2003; Zhang et al. 2014; Neubauer et al. 2015) (CEI:M1 #1; ATI:MD #2). In addition, a second life manufacturer faces high price pressure caused by new and cheaper battery systems that comprise the latest battery technology and that enter target markets as regular battery energy storage systems (Lih et al. 2012; Nykvist and Nilsson, 2015). As observed in the regular battery energy storage system business, the technical complexity of the used battery systems and the hazard potentials that go along with the selection of an inappropriate battery system and an improper installation and operation demand the second life manufacturer to build up a network of trusted trading and service partners that directly interact with the second life customers and contribute with their local infrastructure to the second life manufacturers' business (Bräuer et al. 2016).

Second life customers define requirements for an energy storage system and thus articulate a demand for used EVBs and additional services. Depending on the second life manufacturer's business model, businesses and private end users might be addressed with the product and service offering. The goal of second life customers is to operate energy storage systems and benefit from their operation, for instance, due to an increased energy self-consumption of residential renewable resources or avoided power consumption from the public grid in expensive on-peak times. When acquiring an energy storage system, the customer needs to ponder on the system's initial (purchase) or recurring costs (service fee), on the installation costs, on costs for possible replacements for battery components or complementary power electronics, on maintenance costs, and on the system's expected overall operational life as well as electricity tariffs or achievable service fees, which influence the investment's amortization.

4.3 Resulting transactions and their governance structures

Based on the review of current industrial practice, the listed assumptions, and the inquiry on strategic objectives pursued and core competencies required by key actors that adopt the presented roles, we conclude that trading used EVBs comprises

of two key transactions: automotive OEMs as component suppliers provide used EVBs to second life manufacturers (T1), and second life manufacturers provide a repurposed battery energy storage system and additional services to second life customers (T2). To further detail the identified transactions, we set out to derive possible governance structures. We apply Williamson's (1975, 1979) initial distinction of the market, cooperation, and hierarchy as archetypes of governance structures that are widely recognized in the literature. However, not only Williamson's dimensions of asset specificity, frequency, and uncertainty but also other factors such as a firm's strategic motives and its resources influence the governance structure for a transaction and can thus be used to reason about the possible manifestation of a transaction's governance structure (Hamel 1991; Holland and Lockett 1994; Klein and Kronen 1995). Thus, different governance structures might be suitable for T1 and T2.

4.3.1 Transaction T1: transfer of used EVB from automotive OEM to second life manufacturer

From the perspective of automotive OEMs, the implementation of this transaction in a market setting would be associated with high risks. These risks especially arise from sensitive information that is stored in battery systems and could be exploited by competitors. Moreover, OEMs have to fear potential damages to their brands if battery systems are not adequately repurposed for safe and enduring operation or are utilized in unsuitable second life applications. Consequently, automotive OEMs are strongly interested in retaining control of their data, the repurposing process, and the repurposed battery systems' targeted applications. Conducting this transaction in a market setting would not allow automotive OEMs to retain this level of control.

From the perspective of a second life manufacturer, investments in relationship-specific assets are necessary. The lack of standardization among automotive OEMs, proprietary battery components, and encrypted battery data require second life manufacturers to build up OEM-specific knowledge on the repurposing of battery systems, and EVB-type-specific target designs for the repurposed battery systems need to be developed. In addition, second life manufacturers have to strongly rely on repurposing processes that are optimized for a particular automotive OEM, since the costs for repurposing batteries are a crucial factor in the competitiveness of the repurposed battery systems in comparison to new battery systems (Cready et al. 2003; Neubauer et al. 2015). A second life manufacturer's resulting dependency on an automotive OEM bears the risk of being exploited by the OEM. Consequently, both the automotive OEM and the second life manufacturer have to protect against the opportunistic behavior of the other.

While a hierarchical setting and thus the adoption of both roles by an automotive OEM promises protection against opportunistic behavior, the findings from our interviews indicate that automotive OEMs are rather focused on their core business and aim at transferring their duties associated with an (industrial scale) EVB second life business to a trusted contractual partner. Consequently, we argue that T1 will rather take place in a hybrid setting between market and hierarchy, such as long-term cooperation that will likely build on a detailed contract between an automotive

OEM and a single, specialized second life manufacturer [see also (BRC:BR1 #2)]. The described cases of Renault and Nissan provide practical evidence that these transactions have been implemented.

4.3.2 Transaction T2: second life manufacturers providing energy storage systems to second life customers

The recommended governance structure for T2 depends on the particular second life applications targeted with the repurposed battery systems. While the potential demand for residential and small commercial battery energy storage systems that have the size of a single or a handful of used EVBs is expected to go into the millions or hundred-thousands, the market potential for large-scale applications that build on some hundred used EVBs is likely limited to some dozen installations per region or country (Heymans et al. 2014).

For small-sized second life applications, the competition with regular battery energy storage systems that are sold on increasingly maturing markets is expected to be high (Neubauer et al. 2015). Since customers' requirements towards battery systems are similar and typically solely differ in the systems' performance (e.g., available capacity, provided power, and efficiency), these battery systems are sold as off-the-shelf products and mostly modular expendable products that typically do not require high product-specific complementary investments. Regular systems are expected to have a lifetime of about 15–20 years (Bräuer et al. 2016), while repurposed systems are estimated to reach up to 10 years of operation (Ahmadi et al. 2017; Richa et al. 2017), which strongly limits the transaction frequency between actors. Against this backdrop, we argue for performing T2 in a market setting if the size and complexity of the repurposed battery systems are low. This setting promises the lowest costs for coordinating and administering the transaction, since a low asset specificity is present, and competition from existing markets for regular battery energy storage systems pose an additional barrier to opportunistic behavior.

In contrast, large-scale applications demand the adjustment of some hundred used battery packs that are integrated into a complex battery system, which is typically optimized for a specific grid application, such as frequency regulation, peak shaving, voltage control, or provisioning of an operating reserve. Individual efforts are not only required on the provider's side, who has to engineer the systems based on the customer's particular requirements, but also on the customer's side, who has to invest into application-specific infrastructure, and who has to prepare the installation location to fulfill technical, legal, and regulatory requirements concerning the system's operation and safety (e.g., secured sites with access to medium voltage and possibly high voltage grid). In addition, a second life customer needs qualified personnel to monitor and maintain the repurposed battery system and monetize the battery system's services. Finally, with the complexity of the repurposed battery systems and the number of integrated battery packs also the periodic demand for compatible replacement battery components increases, which is challenging, as the OEMs' battery technologies might change over time. Consequently, if the used EVBs shall be repurposed for large-scale applications, the

presented attributes render a market setting for transaction T2 unfeasible, since the high relationship-specific investments will not be thoroughly protected.

Furthermore, based on the introduced role concepts, we argue against a hierarchical setting, since repurposing the used EVBs and operating several large-scale battery energy storage systems within a single company can be associated with high financial risks. These risks are further aggravated by limited experiences with the actual aging and performance of used EVBs in their second life. Instead, we argue for a hybrid setting that is secured with a detailed contractual agreement as the organizational frame for T2, in case of large-scale applications that might be realized as long-term cooperation between second life manufacturer and second life customer. In this case, the complexity and costs of the individualized solution and minimal cost pressure justify higher transaction costs for contract design.

T1 is assumed to take place between an automotive OEM and a second life manufacturer who close long-term cooperation that is secured by a detailed contract. The governance structure of T2 between a second life manufacturer and a second life customer depends on the size and complexity of the repurposed battery systems. While small-sized battery energy storage systems for residential or small commercial applications are best traded in a market setting, large-scale applications require securing the trading partners’ specific investments, which is best achieved by cooperation between both actors. Figure 1 depicts the resulting simplified value network, which is in the following denoted as cooperation-to-cooperation/market setting.

5 Analysis of information asymmetries and transaction costs

The principal-agent theory as an analytical lens has been applied to examine various contractual relationships, such as general buyer–seller relationships (Pavlou et al. 2007), supplier–distributor relationships (Lassar and Kerr 1996), and insurer–insurer–relationships (Rothschild and Stiglitz 1976). In all these models, it is assumed that the agents have an information advantage over the principals and that both principal and agent are motivated by self-interest, such that both actors try to

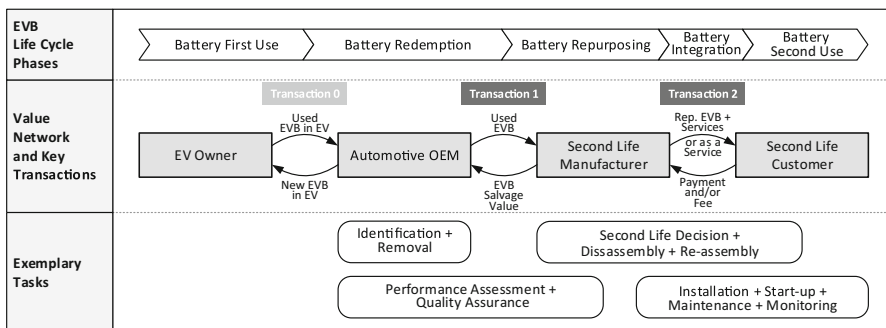


Fig. 1 Battery life cycle, value network, key transactions, and core activities for trading used EVBs

maximize their utility (Jensen and Meckling 1976; Spremann 1987). As depicted above (see Sect. 2), the assumed information asymmetry and opportunistic behavior of both trading parties cause challenges for the transactions, which can be addressed with mechanisms such as screening or signaling, incentive-oriented contracts, or IS support (Spence 1973; Arrow 1986; Spremann 1987; Pavlou et al. 2007). Since we assume that the exchange of the used or repurposed battery system goes along with bilateral obligations, we analyze each transaction as a bundle of two interrelated but opposing principal-agent problems.

Also building on the assumptions of economic self-interest and opportunistic behavior of trading parties, transaction cost theory, amongst others, focuses on the identification of sources for transaction costs, which depend on the dimensions of a transaction and its governance structure (Williamson 1979, 1985). While in transaction cost theory, governance structures are selected based on a transaction’s asset specificity, frequency, and uncertainty (Williamson 1979, 1985), we assume that the governance structures for T1 and T2 are fixed due to the assets and core competencies possessed by the involved partners and that other mechanisms, such as a suitable IS support, have to be found to lower the transaction costs for both trading parties.

We structure the analysis by further distinguishing information asymmetries and transaction costs that occur ex-ante and ex-post contracting. Where appropriate, we illustrate the arguments with properties of EVBs and data from our interviews. We summarize the findings by identifying economic challenges (EC) that should be addressed when implementing the transactions or supporting the transactions with information systems. In the subsequent section, we address the identified challenges by IS design principles.

5.1 T1: transfer of used EVBs from automotive OEM to second life manufacturer

As a starting point for T1, we assume a buyer–seller relationship between an automotive OEM and a second life manufacturer (see Fig. 2, left). In this case, the second life manufacturer as principal and buyer delegates the responsibility for selecting EVBs to be repurposed to the automotive OEM. The automotive OEM provides the second life manufacturer with used EVBs and gets paid for the provision of battery systems. Before the exchange of the used battery takes place, a substantial information asymmetry regarding the performance and longevity (and

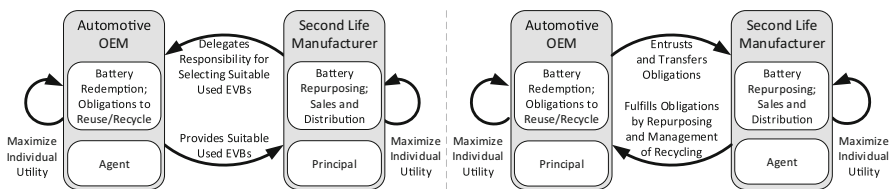


Fig. 2 Principal-agent models for T1: buyer–seller relationship (left) and delegation of obligations (right)

thus quality) of the used EVBs can be observed (hidden characteristics). On one hand, the OEM, who has redeemed the EVBs from the EV owners, can easily obtain data on the EVBs' past usage and their present condition from the EVs' board computer or the used EVBs' battery management system (BMC:PM1°#1; CBR:PE #2; BRC:BR1 #1, CEI:M1°#1). On the other hand, the second life manufacturer strongly relies on an EVBs' quality and remaining performance, since it determines the batteries' suitability for a second life application. However, the second life manufacturer can only retrieve reliable information on the used EVBs' quality after the manufacturer gains full possession of the battery systems, by conducting a time-consuming and resource-intensive manual testing of the battery components (SPR:MD #1; CBR:PE #3; ATI:MD #1) and thus bears the risk of unsuitable or short-lived used EVBs. Consequently, without a signal from the OEM concerning the used EVBs' quality or other mechanisms, Akerlof's (1970) lemon-market problem states that the second life manufacturer, as the buyer will likely assume an average quality, and will only pay an average price. Resulting adverse selection can increasingly drive above-average high-quality used EVBs out of the market and may ultimately inhibit the transaction (EC#1). While the suggested long-term cooperation between OEM and second life manufacturer especially reduces the second life manufacturer's risk to invest in OEM-specific and possibly battery type-specific assets for the repurposing process, the information asymmetry still needs to be addressed by the OEM by revealing the EVBs' usage and condition data before the exchange and by providing a long-term warranty on the battery components or by accounting for the risk of the second life manufacturer with significantly lower prices.

Besides the buyer–seller relationship between automotive OEM and second life manufacturer also a reciprocal relationship can be observed where the automotive OEM as principal delegates obligations to reuse, or repurpose and recycle EV components to a second life manufacturer as an agent (see Fig. 2, right). Considering the present role allocation, the critical information asymmetry between automotive OEM and second life manufacturer occurs after the exchange of the used battery systems. Since the second life manufacturer is interested in maximizing profit but is affected by decreasing prices for new battery components (ATI:MD°#4), the second life manufacturer has to limit the expenses for repurposing batteries.

Consequently, it is attractive for the second life manufacturer to reduce costly but quality-ensuring repurposing activities (e.g., disassembly, inspection, repairs, replacements, and testing) to a minimum. Moreover, instead of integrating costly low-maintenance, fail-safe components and additional safety mechanisms into the repurposed battery systems, maintenance services and remote monitoring might be offered to the customer. Corresponding policies of the second life manufacturer increase the risk of defects, limit the longevity of the battery system, and might also affect the automotive OEM. Even though the automotive OEM delegates his obligations, a negative performance of the second life manufacturer in his tasks of repurposing and recycling used EVBs can rebound upon the OEM and damage its brand (ATI:MD°#3). Overall, the potential revenue from repurposing the used EVBs will only make a very small part of the OEM's business, whereas it is the core

business of the second life manufacturer. One may thus expect the OEM to act rather risk-averse, whereas the second life manufacturer might have to take risks to establish himself as a player on the market. However, despite this risk, the automotive OEM is not able to fully monitor the second life manufacturer’s actions (hidden action). Without a further (financial) alignment of the OEM’s and the second life manufacturer’s interests and the securing of a compliant behavior of both parties, this may lead to moral hazard (EC#2).

5.2 T2: second life manufacturers selling energy storage systems to second life customers

The analysis of T2 again starts with the assumption of a buyer–seller relationship, this time between second life customer as principal and second life manufacturer as agent (see Fig. 3, left). The second life customer entrusts the second life manufacturer with providing an SLBESS that builds on used EVBs. The customer desires a system that fulfills his requirements and can be operated reliably and safely. In the case of purchasing the battery system, minimal expenditures for maintenance, replacements, and adaptations over a long period ensure that the initial investment is worthwhile for the second life customer. In contrast to this, the second life manufacturer operates profitably with minimal expenditures for the quality-ensuring repurposing activities and additional components and benefits from additional earnings from complementary services, such as maintenance and remote monitoring. This conflict of interests is further aggravated by an ex-ante information asymmetry. While the second life manufacturer can test the battery systems concerning their performance and—with increasing sales of similar SLBESS—gradually gains experience in how the systems age over use and time, most second life customers lack the required knowledge and experience to judge the battery systems’ quality and fit to their requirements. Consequently, even if the second life manufacturer provided them with corresponding data on the systems’ past usage and present status before the conclusion of the contract or the transfer of the good, the second life customers would have to rely on the second life manufacturer to interpret these data and to engineer or choose battery systems that fulfill the customers’ particular requirements (hidden characteristics) (EC#3). While a long-term cooperation with a detailed contract as suggested for complex SLBESSs might limit the second life manufacturer’s incentives for opportunistic behavior (Lassar and Kerr 1996), a market setting might have less incentives for non-opportunistic

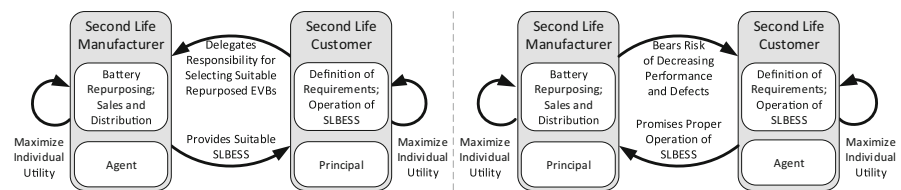


Fig. 3 Principal-agent models for T2: buyer–seller relationship (left) and quasi-insurant–insurer relationship (right)

behavior so that the establishment and preservation of a trade between second life manufacturers and second life customers strongly depends on countermeasures such as signaling. Signaling can be achieved by the second life manufacturer by offering long-term warranties or, as suggested above, by remaining the owner of the SLBESS and operating use-oriented (e.g., pay-per-use) or result-oriented (e.g., provision of functional result) business models where the second life manufacturer thus bears the risk of defects (Bräuer 2016; Bräuer et al. 2016). Otherwise, adverse selection and market failure might be the result (Akerlof 1970).

Further ex-ante challenges that occur in this second transaction relate to transaction costs. For issuing a quote and providing fitting SLBESSs, the second life manufacturer requires both, detailed usage and status data of the used EVBs as well as information on the customers' requirements towards the repurposed battery systems. Thereby, the corresponding transaction costs depend on the ex-ante information asymmetry in T1 (hidden characteristics) and the OEM's willingness to share battery data as well as the completeness of these data. In the case of incomplete data, manual tests will lead to a significant increase in the corresponding ex-ante transaction costs for generating a quote (ATI:MD^o#1). A similar cost driver is the clarity of the customers' requirements towards the SLBESSs, which, especially in the case of inexperienced customers, need to be elicited by the second life manufacturer. Consequently, the second life manufacturer faces transaction costs for issuing a quote that depend on the extent, quality, and usefulness of available battery data and requirements provided by the customers (EC#4).

The second life customer, on the other hand, faces transaction costs for searching and choosing a supplier for the BESS (EC#5). After having identified the need for a BESS, the second life customer will evaluate available offers on the market, also choosing between SLBESS and regular BESS. The effort taken to receive the final quote as the basis for the agreement, e.g., comparing various suppliers and their products, identifying his requirements towards the BESS, are ex-ante transaction costs for searching for the trading partner and for drafting and negotiating the agreement (Williamson 1985; North 1990).

Beside the seller–buyer relationship between second life manufacturer and second life customer, the provision of a warranty or the offering of the SLBESS as a service, where the product liability stays with the OEM, can be interpreted as a quasi-insurance on the battery system's performance that is issued by the second life manufacturer as principal to the second life customer as agent (see Fig. 3, right). Considering the present role allocation, the critical information asymmetry occurs after the conclusion of the contract. Safeguarded by the warranty or the service contract, the second life customer might reduce his care in the operation of the BESS or might not operate the battery system by the contract's or warranty's terms and conditions. An agency problem occurs as the customer's actions are typically not observable by the second life manufacturer, who, however, has to pay for the repair or replacement of the battery components (hidden actions) (Arrow 1986) (EC#6).

All six challenges of the transactions T1 and T2 are summarized in Table 2.

Table 2 Summary of economic challenges (EC) induced by information asymmetries and transaction costs

	T1: OEM to second life manufacturer	T2: second life manufacturer to second life customer
Ex-ante	EC#1: OEM > SLM. The SLM cannot assess the EVB's quality without facing high costs (hidden characteristics). This lack of information can lead to adverse selection and may prevent the transaction.	EC#3: SLM > SLC. The SLC relies on the SLM to engineer or choose battery systems that fulfill their requirements (hidden characteristics). EC#4: The SLM's transaction costs for issuing a quote on product and service offering depend on the extent, quality, and usefulness of available battery data provided by OEM and requirements provided by the SLC. EC#5: The SLC faces transaction costs for searching for and choosing a supplier and a suitable offering for the SLBESS.
Ex-post	EC#2: OEM < SLM. The OEM is not able to fully monitor the SLM's actions (hidden action), who can act against the OEM's interest (moral hazard).	EC#6: SLM < SLC. The SLM is not able to observe the SLC's treatment of the SLBESS (hidden action). This lack of observation can allow the SLC to exploit the situation (moral hazard).

OEM automotive original equipment manufacturer, *SLM* second life manufacturer, *SLC* second life customer

6 information systems design principles

The identified economic challenges mainly arise from asymmetric information (EC#1, 2, 3, 6) and high transaction costs (EC#4, 5). If designed appropriately, information systems can be used to reduce or even remove information asymmetries and lower transaction costs (Cordella 2006; Dimoka et al. 2012). To guide the design of appropriate information systems, we propose five design principles that resolve the six challenges identified in our conceptual analysis. In line with up-to-date findings in design science research, each design principle includes a specification of its form and function, activities to be supported, and the boundary conditions (Chandra et al. 2015; Seidel et al. 2018). Moreover, while some of the presented design principles support both transactions (DP 1), others address challenges that occur in either T1 (DP 5) or T2 (DP 2–DP 4) (see Table 3).

The overall boundary conditions for the design principles are constituted in an area of conflict. On the one hand, all participating actors represent self-contained entities and thus aim at maximizing their individual utility based on the set of available information. On the other hand, the business relations between the actors are shaped by mutual dependency and thus require compromises and agreements to establish and maintain an EVB second use business for mutual benefit. Information systems support for the business transactions might be established in the range between a single holistic and centrally operated system with smaller connected, actor-individual counterparts and an entirely decentralized information systems

Table 3 Overview of design principles (DP) to remedy transaction-related economic challenges (EC)

		T1		T2			
		EC#1	EC#2	EC#3	EC#4	EC#5	EC#6
		Hidden char. of used EVBs	Hidden actions of SLM	SLC has to rely on SLM	Ex-ante transaction costs of SLM	Cust. search costs for suitable SLM	Protection against exploit. of warranty
DP 1	Support the import, storage, processing, and distribution of battery-related data	X			X		
DP 2	Implement two interrelated decision-making processes			X	X		
DP 3	Provide external users access to the product and service catalog					X	
DP 4	Log, transfer, analyze, and distribute data from second life applications		(X)				X
DP 5	Report on EVBs' repurposing and further use		X				

X fully addressed, (X) partly addressed

infrastructure. The following design principles remain valid, even for opposing infrastructural approaches, but need to be interpreted and coined to the individual setting.

6.1 DP 1: support the import, storage, processing, and distribution of battery-related data

Due to the complexity and individual aging behavior of EVBs, storing structured data on each EVB is crucial for both T1 and T2. The availability of data on individual EVBs can be assumed to decrease information asymmetry for all actors. In T1, the OEM can use these data to signal an EVB's quality to the second life manufacturer and to counter adverse selection that might occur due to asymmetric information (EC#1). In T2, structured data can reduce the transaction costs of the second life manufacturer for preparing an offer for an SLBESS (EC#4).

Battery data comprise master data, usage data, and condition, respectively, status data (Klör et al. 2015b). Master data are required to identify the battery's structure

and properties. Usage data documents how exactly an EVB has been employed during its first life in the EV. Status data describe the removed EVB's current properties. Combined, these data are essential to understanding reconfiguration options, to determine past and likely future aging behavior, to decide on the EVB's suitability for repurposing, for a fitting application scenario, and for complementing services.

While master data on EVBs might be (partly) publicly available in specifications (e.g., Federal Institute for Materials Research and Testing 2013), data on an EVB's usage history and status can be stored (typically encrypted) in the EV's board computer or BMS. Already during the EVB's first automotive life, an information system might receive these data at constant intervals via the Internet or the data is imported to the information system during a (scheduled) maintenance. In both cases, downstream information systems need to implement interfaces to import the data, and the definition of a common data logging and exchange standard for battery data could facilitate an inter-system data exchange. To comply with the OEM's desire of protecting crucial information on battery aging as well as to conform to increasingly stricter data protection regulations (e.g., as entailed by the new European Data Protection Regulation, GDPR), the information systems need to implement means of encrypting, anonymizing, and/or aggregating data as well as processing these data (including the decryption).

In matters of data encryption, value network-encompassing concepts need to be developed. To this date, data encryption of battery usage and status data is already enforced by the automotive OEM during the EVB's first automotive life to ensure that only authorized dealers, or workshops can access this sensitive data. However, for the subsequent handling of data encryption during the EVB's second life, various options are available. For instance, if the whole battery system (including especially the BMS) is to be repurposed without a change of encryption or the re-encryption of data, the OEM needs to grant the second life manufacturer (as well as possible service providers) access to the specific keys. Alternatively, the BMS might be replaced by the second life manufacturer, which offers the opportunity to re-specify data encryption. While the first approach bears the advantage of reduced repurposing costs, the remaining actors are exposed to the automotive OEM. The second approach grants the second life manufacturer more independence. However, it also leads to increased costs for developing or purchasing a suitable BMS and for replacing the BMS during repurposing.

In terms of data aggregation, the actors need to find a trade-off between a detailed logging of battery events, which possibly offers the best basis for decision-making but also leads to huge amounts of to be transferred and processed data, and the deliberate omitting of details and thus a loss of accuracy but a gain of privacy and protection of interests. For instance, Menne et al. (2019) suggest an aggregation with minimum space requirements that builds on a mixture of recording some parameters on a quasi-continuous basis, while other parameters are logged in an event-based fashion, e.g., when a strong discharge current occurs during start-up (see Table 4). Parameters are logged for the battery pack and individual battery modules. For further reducing the amount of data, measurement ranges are defined

Table 4 Overview of key battery parameters to be exchanged between systems (Menne et al. 2019)

	Battery status parameter	Battery usage parameter
Quasi-continuous logging	Capacity (with date and time) Internal resistance (with date and time)	Operating time
Event-based logging	Rate of self-discharge	Current load Depth of charge/depth of discharge Operating temperature Full cycles

for selected parameters (based on experience) and simple registers can be used for counting the number of occurred events.

A key challenge relates to the integrity of battery data. Like the mileage of a used car, an EVB's quality and expected remaining lifetime, and thus, its economic value strongly depend on its usage history and its status. Gaps in documenting the battery's usage history can easily occur, e.g., caused by errors during logging or transferring the data, both within the EV as well as when communicating with external information systems. However, also a willing manipulation of battery data appears to be tempting, particularly in distributed environments. Blockchain technology might be used to secure the integrity of the battery data, e.g., by storing the data in a blockchain-based database (Gaetani et al. 2017) or networks (Hua et al. 2018). Especially if, in the future, the trade of used EVBs might take place on rather open marketplaces (like for other used car parts) (Klör et al. 2015a), a blockchain-supported battery pass might signal the battery data's integrity and thus allows to build trust between buyers and sellers. Despite possible strengths, the general public's perception of the blockchain as a quasi-tamper-proof technology might also be exploited to feign integrity and correctness of data that is, in fact, not existent. If erroneous, incomplete, or manipulated data are stored in the blockchain in the first instance, challenges resulting from asymmetric information cannot be settled but rather deteriorate. Consequently, above all, information systems need to ensure that decision-makers (such as the second life manufacturer) can access correct, relevant, and reliable data, so that their tasks can be carried out effectively and efficiently. Correspondingly:

DP 1: provide features to import, store, process, and distribute EVB-related information in the form of possibly encrypted, anonymized, and aggregated master data, usage data, and status data while ensuring data integrity, so that a decision-maker can access and judge an EVB's quality without the (immediate) need of testing the EVBs manually, and so that further repurposing tasks can be carried out effectively and efficiently.

6.2 DP 2: implement two interrelated decision-making processes

In T2, amongst data on the used EVBs, the second life manufacturer needs information on the requirements the customer, respectively, the application scenario place on an SLBESS and on complementing services (EC#5). Collecting these requirements as well as matching requirements and available EVBs results in information gathering costs and costs for issuing a quote (EC#4). Performing an efficient matching using an information system lowers the efforts required for selecting appropriate batteries and, thus, reduces a second life manufacturer's transaction costs. Associating EVBs and scenarios can be described as a bipartite matching problem that can be solved using linear programming decision models to increase the quality and speed of the decision-making process (Klör et al. 2018).

A reliable matching that is driven by negotiated technical objectives and thoroughly documented signals the SLBESS's quality to the customer and thus helps to mitigate the information asymmetries between second life manufacturer and second life customer (EC#3). Furthermore, since this information asymmetry might lead to adverse selection and could prevent T2 (EC#3), the second life manufacturer can offer services such as warranties to signal the SLBESS's quality. Since the requirements of second life applications are diverse, and the combinatorial complexity of bundling SLBESS and services is high, providing quotes for individually configured product-service offerings forms a complex additional decision task and might entail substantial transaction costs (EC#4).

An information system that recommends additional services to complement an SLBESS and that ensures the validity of product-service configurations can help to reduce transaction costs. As depicted by Klör et al. (2017), such a system can provide a rule engine that uses pre-defined configuration rules to identify valid or invalid configurations. Configuration rules can either exclude or include services or additional product components based on pre-defined conditions. In addition, a data-driven recommender system can propose value-added services that are likely to be bought by a customer. To implement this system, the battery and scenario types as well as the technical deviations of battery and scenario can be used as a similarity metric to select the data on which recommendations should be based (Klör et al. 2017). Correspondingly:

DP 2: integrate means for supporting the two interrelated decision-making processes of matching used EVBs and second life applications and configuring fitting product-service offerings, so that a decision-maker is (partly) relieved of the task of manually determining fitting or even optimal assignments and configurations, and so that the process is thoroughly documented and (fairly) comprehensible.

6.3 DP 3: provide external users access to the product and service catalog

In T2, potential second life customers face search costs to identify suitable second life manufacturers (EC#5) that offer fitting product-service configurations. To address these costs, two approaches are favorable: On the one hand, the second life

manufacturer can publish information about the offered SLBESS and services on the internet. Strategies to share correspondent data might include publishing (a subset of) the battery master data and service master data for search engines that are run by content aggregators. Alternatively, the second life manufacturer might allow customers or intermediaries such as local electricians, which are a common part of the distribution channel in the residential BESS business (Bräuer et al. 2016), with a web-based or app-based configurator to directly specify the second life applications' requirements, choose from component alternatives and value-added services, and finally ask for a quote.

The data need to be provided in a structured format (e.g., XML, JSON), for instance, based on the meta-model for describing EVBs presented by Klör et al. (2015a, b). Common protocols for web services (e.g., SOAP, REST) can be used to make the data accessible to external information systems and stakeholders. The data should at least include the SLBESS's technical specifications and information on any value-added services offered. Correspondingly:

DP 3: provide access to data on the SLBESS and value-added services and offer audience-specific functionalities for specifying second life application requirements and selecting preferred services, so that prospective buyers, component providers, and service providers can access the product and service catalog and trigger the decision-making process.

6.4 DP 4: log, transfer, analyze, and distribute data from second life applications

In T2, the second life manufacturer faces the risk of exploitation of warranties by unjustified claims due to the customer's self-interest (EC#6). By tracking the SLBESS's usage at the customer's side, the second life manufacturer can guard against customer claims that result from intended or unintended misuse of the repurposed EVBs, particularly in use-oriented and result-oriented business models in which the second life manufacturer is responsible for ensuring the battery system's serviceability. Thus, key usage parameters (e.g., see Table 4) need to be reported to the second life manufacturer and might be further stored and processed.

The battery's usage can be recorded by directly capturing the BMS data streams or by relying on additional sensors and devices (e.g., provided by solar inverters). For transfer, both a (continuous) connection via Internet or a manual readout during maintenance are possible. From the second life manufacturer's side, data integrity and authenticity are essential to assure that the data have not been tampered with. For example, a transport layer security (TLS) can be protected with asymmetric public key cryptography to authenticate the BMS and the information system of the second life manufacturer, while message authentication codes (MACs) can be used to verify data integrity. In addition, symmetric cryptography can be used to assure confidentiality over public networks. It is important that both the server and the client authenticate themselves to the respective other.

Moreover, changes in major regulations demand data minimization, i.e., a strict limitation of collected and processed personal data to a stated purpose, and,

furthermore, require the controller and/or processor to clearly and plainly illustrate the purpose to the data subject (Art. 5 ff. General Data Protection Regulation GDPR). Those information systems that process personal data need to “implement appropriate technical and organizational measures to ensure a level of security appropriate to the risk” (Art. 32 (1) GDPR), this includes, amongst other things, pseudonymization and encryption.

Again, blockchain technology might be used to ensure data integrity and thus limit the actors’ means of manipulating the usage data. However, considering the new data protection regulations, blockchain technology might also be used to protect SLBESS’ user’s personal data and ensure ownership (Zyskind et al. 2015). Coupling blockchain technology and an off-blockchain data storage solution, SLBESS’ users as owners of their personal data might directly and individually control the permissions of contractors, such as the second life manufacturer or service providers, to access and process selected data, and remain the unmistakable owners of their data, even if the SLBESS’ usage data is hosted by a third party or distributed among actors. Correspondingly:

DP 4: offer means of logging the SLBESS’ usage in its application as well as transfer, analyze, and distribute the data corresponding to data protection regulations and data integrity requirements, so that component and service providers can meet their contractual obligations and secure from wrongful claims.

6.5 DP 5: report on EVBs’ repurposing and further use

In T1, the OEM’s inability to monitor the actions taken by the second life manufacturer may lead to a moral hazard (EC#2). Reports can be used to signal that the EVBs supplied by the OEM were repurposed successfully and in line with the OEM’s strategy and brand and might allow a lowering of the OEM’s monitoring costs. Based on these reports, the OEM can document legal compliance with obligations to take back and handle used EVBs. In addition, reporting can be used to provide the OEM with second life usage data. Thereby, data anonymization, aggregation, and access management are required to protect the second life customers’ privacy (also see DP 4).

The second life manufacturer can implement business reporting as a business intelligence (BI) system. The system should integrate all available data on a battery over its whole life cycle, especially including the usage data of its first life (see DP 1), data on the targeted second life application’s requirements (see DP 3), and data on its use during its second life (see DP 4) as well as the matching and configuration decision (see DP 2). Since different stakeholders and users are involved, reports should be used flexibly to satisfy idiosyncratic information needs. The data sources can be queried periodically since no real-time requirement is existent. Some of the reports can be made available to the OEM for compliance and to provide them with the opportunity to optimize and design their EVBs for a second life. For this purpose, suitable interactions routines and role concepts have to be implemented. Furthermore, the system can be used to document and report the

disposition (especially the professional recycling) of a battery to governmental institutions. If regulations require the documentation of a battery's disposal, a challenge is to document reconfigured batteries for which components from different EVBs were used.

Alternatively, a digital battery pass might be implemented. Like a life cycle record for machines or other technical objects (see for instance Deutsches Institut für Normung e.V. 2017), the battery pass is issued with the production of the EVB for its first life and contains a record of key master data, status data, and usage data that is continuously updated throughout the battery's operational life (Infineon 2012; Menne et al. 2019). Again, for ensuring the pass' integrity and restricting the access to sensitive data to appropriate stakeholders over the boundaries of a single life cycle phase, blockchain technology might be used (see DP 1 and DP 4). Correspondingly:

DP 5: support the stakeholder–individual reporting of key battery data, including data on the batteries' first life, on the application scenarios' requirements, on the decision-making process, and on the batteries' second life as well as on the possible redemption and recycling, so that disclosure and submission requirements can be satisfied.

7 Conclusion and outlook

The contributions of this paper are twofold. First, the review of current industrial practice and the statements made by our informants in the in-depth interviews suggest that trading used EVBs will likely take place in a cooperation to cooperation/market setting, which includes automotive OEMs, second life manufacturers, and second life customers as central actors. Reviewing the properties of this trade against the backdrop of new institutional economic theory led us to identify six economic challenges that must be addressed when attempting to establish and sustain this trade. Second, in line with these challenges, we proposed five design principles that information systems must implement to enable trading used EVBs.

Subsequent research can build on our results to further analyze inter-organizational dependencies between actors that participate in value networks for trading used EVB. Moreover, our results support the design and evaluation of information systems that allow for establishing a trade of used EVBs. As regards design, the design principles guide software developers in specifying and implementing the core functionalities that are required. As regards evaluation, each design principle refers to statements that can be empirically tested once a trade of used EVBs will have emerged. In this way, further research can elicit if and to what extent information systems that are built concerning the proposed design principles can help to reduce or avoid the inter-organizational challenges identified by principal-agent theory and transaction cost theory.

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