Comput Sci Res Dev (2017) 32:195–209
DOI 10.1007/s00450-016-0306-7

SPECIAL ISSUE PAPER

Ensembles of context and form for repurposing electric vehicle batteries: an exploratory study

Completed Research Paper

Daniel Beverungen[1] · Sebastian Bräuer[2] · Florian Plenter[2] · Benjamin Klör[2] · Markus Monhof[2]

Published online: 9 July 2016

Abstract The electric vehicle battery is the crucial component in electric vehicles. It propels the vehicle's engine and causes around 25 % of the vehicle's overall costs. Unfortunately, due to deterioration, the battery's use gradually restricts the vehicle's driving range, acceleration, and charging speed over time. Only a battery replacement restores the vehicle's performance. Despite its deterioration, the used battery can be repurposed to serve as a battery energy storage system in less demanding second-life application scenarios. Examples are home storage solutions for energy from photovoltaic panels or larger buffer storage solutions for stabilizing energy from wind parks or solar farms. With strongly increasing numbers of electric vehicles world-wide, some hundred thousand aged batteries can be assumed to be available soon. Considering the necessity for a reliable fit of the targeted second-life application scenario (as context) and the battery energy storage solution built from aged batteries (as form), the decision for which scenario a battery should be repurposed needs to be supported by information systems. Since current research falls short of identifying and prioritizing the requirements that characterize second-life application scenarios, information system developers lack justificatory knowledge to guide and constrain the design of corresponding information systems. In an explorative multi-method study, we set out to identify the requirement categories and metrics that need to be elicited for repurposing batteries. The study (a) contributes a prioritized list of requirement categories and metrics for repurposing batteries, and (b) documents how they were instantiated respectively why they were important in an analyzed case.

Keywords Green IS · Battery second use · Requirements · Case study · Electric vehicle battery · Battery energy storage system

✉ Daniel Beverungen
daniel.beverungen@uni-paderborn.de

Sebastian Bräuer
sebastian.braeuer@ercis.uni-muenster.de

Florian Plenter
florian.plenter@ercis.uni-muenster.de

Benjamin Klör
benjamin.kloer@ercis.uni-muenster.de

Markus Monhof
markus.monhof@ercis.uni-muenster.de

1 University of Paderborn, 33098 Paderborn, Germany

2 University of Münster-ERCIS, 48149 Münster, Germany

1 Introduction

Today, light-duty vehicles such as passenger cars and vans account for around 15 % of EU's emissions of CO_2 [1]. An increased diffusion of electric vehicles (EVs) that are powered by renewable energy is one option to reduce the CO_2 emissions and to transform private transportation towards ecologic sustainability [2,3]. Unfortunately, the world-wide spread of EVs still lags behind expectations. Causes include range limitations of EVs, their inconvenient charging because of a fragmented charging infrastructure with incompatible charging standards, and their high initial costs in comparison to traditional vehicles [4,5].

A huge share of these additional costs for EVs is caused by the electric vehicle battery (EVB). An EVB is a complex but modular system, at least consisting of interconnected lithium-ion cells for powering the EV's engine, a battery management system for governing the charging and discharging of the cells, a thermo-system for managing the battery's temperature, and a casing for protection against damages [6]. Despite constantly decreasing costs for battery cells and battery systems as a whole [7], lithium-ion batteries—as dangerous goods—require specific qualifications and safety measures to be put into place, resulting in comparable high costs for handling batteries. Moreover, after about 8–10 years of operation in EVs or at least 120,000 km driven, progressive cell degradation by time and use leads to decreased cell capacities (impeding the car's range) and an increased internal resistance (decreasing an EV's acceleration and charging speed) [8]. Automotive manufacturers then recommend a battery to be replaced, so that it becomes available for an end-of-life treatment.

Repurposing a battery for and further using the battery in a less demanding second-life application scenario is a viable way to use the batteries more efficiently and decrease the overall lifecycle costs of EVBs [9–11]. Possible options include the use as a stationary (i.e., permanently installed) energy storage solution, e.g., for buffering energy from renewable sources, as a semi-stationary (temporary installed) storage, e.g., for powering construction sites, or a mobile application in less demanding vehicles such as an electric wheelchair. Early proof-of-concept studies are currently conducted by first movers, including BMW [12] and Chevrolet [13]. Forecasts predict the global market for second-life EVBs to steadily grow from a volume of $16 million in 2014 to around $3 billion in 2035 [14] or of more than $2 billion as soon as 2022 [15]. Repurposing might also lower the total cost of owning an EV and therefore improve their competitiveness [10,16].

With an increasing amount of used EVBs available for repurposing in the 2020s, the repurposing of EVBs will need to be supported by information systems (IS). In the narrow sense, an IS forms an application system, respectively application software that supports people in their task [17]. The requirement of an IS support especially holds for the task of finding a fit between a targeted second-life application scenario with individually requirements (as context) and a battery energy storage system built from individually aged batteries (as form).

The emerging energy informatics research field allows the IS' scientific community to address challenges of environmental sustainability and to foster Green IS in education and research [18,19]. Following a solution-oriented view on IS research, IS shall be designed to support sustainability [20], for instance, by enabling new sustainable business models. Simultaneously, it is a prime tenet of design science research (DSR) that IT artifacts need to be developed in line with theories as justificatory knowledge [21,22].

Unfortunately, the topic of repurposing and further using EVBs still lacks such knowledge. Existing literature from the electrical engineering discipline deals with, e.g., environmental effects of repurposing EVBs [23–25], cost or lifetime considerations for repurposing batteries [11,26–28], or the identification of theoretical repurposing options and their general technical feasibility [8,29]. However, with the exception of [16,30], data from actual demonstration or prototypes is scarce. Moreover, current research remains vague about specific requirements for designing IS and supporting the task of matching batteries to scenarios. We assume that the self-conception of the discipline warrants Green IS researchers to develop the kernel theory respectively justificatory knowledge [21,31] required for designing IT artifacts themselves, if such theory is not provided by disciplines outside of IS.

Consequently, we set out to identify and systematize the requirement categories and metrics that are relevant for repurposing EVBs. For that, we investigate two research questions:

1. What requirement categories and metrics must be elicited when attempting to repurpose an EVB?
2. How were the requirement categories and metrics instantiated in a smart home scenario and why were they found to be relevant or irrelevant?

The research questions are answered in a multi-method study, including a Delphi study with a panel of 20 battery experts and a case study on the *EfficiencyHouse Plus*, a unique and revelatory case in which parts of an EVB were used to form a repurposed battery energy storage system for a smart home context.

As a description of context, our results contribute to much-needed empirical insights to Green IS research. IT artifacts whose design and evaluation is informed by our results include data structures for describing and discriminating among second-life application scenarios, decision rules for matching EVBs to second-life application scenarios, and quantitative optimization models for identifying the "best" available EVB for each second-life application scenario.

The paper comprises five sections. In Sect. 2, we introduce the topic of sustainability research in IS, handling used EVBs, and requirements engineering. In Sect. 3, the research method is introduced and justified. In Sect. 4, we present evidence from our Delphi study and from the *EfficiencyHouse Plus* case, in which EVB modules were repurposed to form a stationary energy storage system. Moreover, data from both approaches are triangulated to compare a priori assumptions on the requirements that stationary second-life application scenarios impose on EVBs with a posteriori experiences from the *EfficiencyHouse Plus* case. Section 5 concludes the paper.

2 Theoretical background

2.1 Sustainability in IS research

Sustainability refers to balancing financial success and societal goals [32]: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [33]. Organizational sustainability includes *natural environment*, *society*, and *economic performance* [34,35], all of which need to be pursued in parallel [36].

With "Green IT/Green IS" [37], IS research sets out to connect researchers from various disciplines in their collaborative effort to overcome our society's grand challenges of global warming and the shortage of resources [20,38]. Whereas "Green IT" applies a technology-driven perspective that is argued to be "[…] mainly focused on energy efficiency and equipment utilization" [18], "Green IS" more generally "[…] refers to the design and implementation of information systems that contribute to sustainable business processes" [18]. As a sub-field of the Green IS movement, "Energy Informatics" addresses the energy sector itself [39] and aims at "[…] analyzing, designing, and implementing systems to increase the efficiency of energy demand and supply systems" [19].

However, even if first contributions in "Energy Informatics" are available, "Green IS" research that targets sustainability by addressing the electrification of transportation is currently not even represented by a specific (internationally acknowledged) term. We propose to set up a solution-oriented research stream in "Green IS" that focusses on analyzing, designing, and implementing information systems for electric mobility in close reference to electronic and automotive engineering, battery research, and IS acceptance research.

2.2 Repurposing EVBs and other end-of-life strategies

Extending the lifespan of an EVB beyond its automotive life is based on the reason that an immediate recycling of a lithium-ion-based battery is less profitable than other end-of-life strategies. Typically a battery's first life ends when an owner brings the EV to a car dealer or workshop because its performance has become insufficient [24,29]. Experts assume that this occurs when the battery's residual capacity has dropped to 80 % after about 6–8 years of operation [8,40]. In terms of an EVB's lifecycle value, literature recommends an even later (70 % of capacity) or earlier removal from the vehicle, depending on the requirements of the market for used batteries [41,42].

The car dealer respectively the specific OEM or a representative can choose from several strategies for handling a used EVB (Fig. 1). In case of a battery defect that can be easily solved and an otherwise unimpaired functionality, a *repair*, which includes a limited disassembly and a fixing respectively replacement of broken parts [43], allows the battery to continue its first life. If the battery, for instance, has been removed from a broken car but has remained undamaged, *reusing* the battery in a similar car might be possible. Alternatively, the battery might be *remanufactured for reuse*, which demands a complete disassembly and includes the cleaning, inspection, and replacement of components to reach a like new condition, as often done with other automotive components [44]. However, remanufacturing EVBs still is rather expensive, such that its economic feasibility is uncertain [44,45]. If an automotive usage is not feasible anymore, the battery might be *repurposed for further use*, i.e., for a second-life application scenario [8,10,11,46]. Following Ahmadi et al. [8] repurposing "[…] involves a limited level of disassembly, testing for degradation and failure, packaging the batteries for second use, and adding electrical hardware, con-

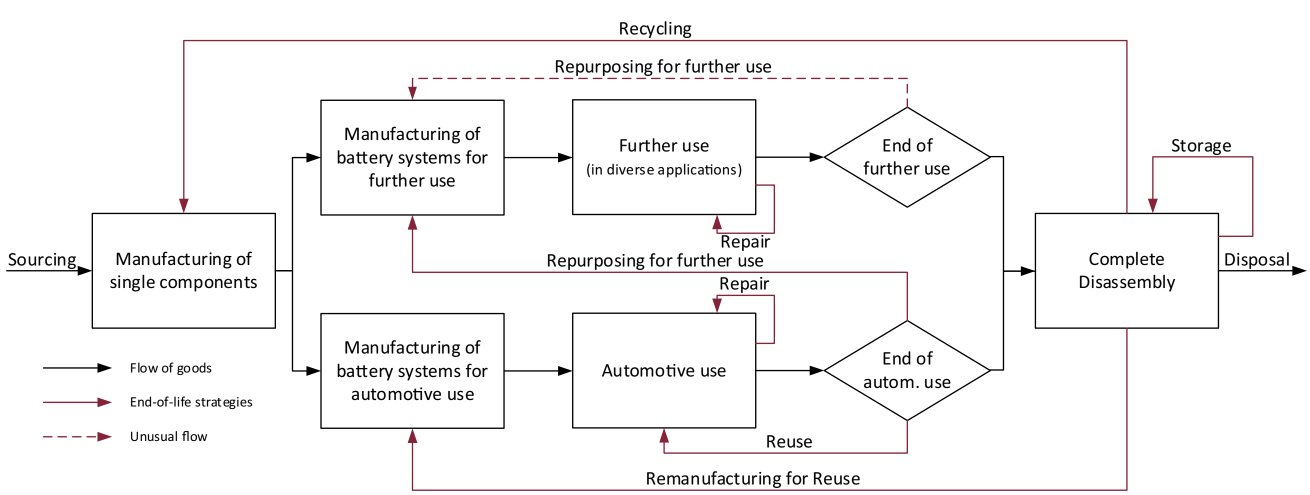

Fig. 1 End-of-life strategies for used EVBs (following Ramoni and Zhang [44])

trol systems, and safety systems to the re-purposed packs". Additionally, "[…] safety systems and packaging have to be added to account for potential moisture exposure, fire protection and other risks or hazards that vary from the vehicle use" [8]. In case that an EVB can neither be remanufactured nor repurposed, *recycling* allows to lead parts or raw materials back to the manufacturing process of the components [47]. Additionally, non-recyclable materials must be disposed (*disposal*). Finally, *storing* EVBs or its components can be reasonable if prices for used EVBs are expectedly rising in the future.

Currently, the most promising end-of-life strategy seems to be the *repurposing* of used EVBs and their *further use* as battery energy storage systems in non-automobile second-life application scenarios. According to the energy storage system's degree of mobility the second-life application scenarios can be categorized in stationary [e.g., home storage for energy from photovoltaic (PV) panels], semi-stationary (e.g., power for stage equipment or construction sites), or less demanding mobile (e.g., scooter, golf car) scenarios.

In *stationary scenarios*, Stan et al. [48] argue that *energy applications* focus on high capacity and charge–discharge cycles that span several hours, whereas cycles in *power applications* span seconds to minutes and many cycles per day. A third category covers applications for *power bridging* and typically demands discharging times of minutes to hours [49,50]. The bandwidth of proposed applications ranges from load following for households, factories, or EV chargers, where battery systems allow to store energy from PV panels or energy that has been (cheaply) obtained from the grid and release it during periods of high energy consumption [29,30,40,51,52], over the provision of backup power (e.g., uninterruptible power supply) [29,48] to stabilizing the energy flow generated from regenerative sources (e.g., in wind or solar parks) [50,53,54]. The research addresses varying sizes of the energy storage systems suitable for private households (1–10 kW and 3–20 kWh), household communities (ca. 25 kW and 50 kWh), stores (400–500 kW and 500–1.000 kWh), office buildings (200–2.000 kW and $<$6.000 kWh), or bigger applications for the energy grid ($>$1 MW and $>$1 MWh), composed of hundreds of EVBs. However, most research on these applications is highly theoretical and lacks empirical proofs from successful applications.

Mobile scenarios, including light EVs [46], electric scooters, floor-borne vehicles, or larger power tools, are rarely considered [55,56]. They often specify tougher requirements than stationary scenarios, since the available space and maximum payload are limited and legal regulations restrict the use of according vehicles in public traffic.

In between mobile and stationary scenarios, the *semi-stationary scenarios* target the temporary setup of larger energy storage systems in movable containers for compensating missing energy infrastructure, e.g., on construction sites, at festivals, or refugee camps [57].

For several reasons matching used EVBs to second-life application scenarios is a complex decision task that needs to be supported by IS. First, each battery's individual usage during its first life leads to a unique battery condition and expected performance and lifespan in its second life [8,9,46,48,58]. Second, a battery's modular character allows the battery's repurposing *en bloc*, its decomposition into its sub-systems, or its combination with other similarly aged batteries to fulfill the requirements of second-life application scenarios. Third, the battery's characterization as a hazardous good, which may imply severe consequences of a potential misconfiguration, increase the importance of a reliable technical fit of second-life application scenario and repurposed battery system, despite a huge number of parameters that have to be considered. The battery's characterization also strongly restricts the handling of repurposed battery systems by non-experts. Consequently, depending on the second-life application scenario and the particular customer, specific services, such as the transport, start-up, monitoring, or repairing have to be performed by experts [59]. Costs for these services need to be taken into account for assessing the economic feasibility of potential assignments of batteries to scenarios and thus further influence the decision task's complexity.

2.3 Requirements for specifying ensembles of form and context

In his book on the synthesis of form, Alexander [60] observed that

> "[…] *every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to the problem; the context defines the problem. […] when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context. Good fit is a desired property of this ensemble which relates to some particular division of the ensemble into form and context*" [60].

Design problems only occur in situations in which a field description, i.e., a "unitary description of the context" is absent, since the properties of a form would directly and unambiguously be determined by this field description without any degrees of freedom for designing the form [60]. One way to conceptualize properties of a context is to specify a set of requirements that characterize the context (even if this list is infinite by definition), trace any potential misfits of the context and the form, and resolve the misfits by altering the design of the form [60].

The term *requirement* refers to "[…] a condition or capability that must be met or possessed by a system, product, service, result, or component to satisfy a contract, standard, specification, or other formally imposed document" [61]. *Functional requirements* describe specific functions or tasks that a system must execute or support [62], defining how the system should respond to specific inputs and environmental conditions [63]. *Non-functional requirements* detail functional requirements by evaluating the operation of a system or its development process [62,64]. While functional requirements refer to a specific system component, non-functional requirements refer to interdependent components or to the system as a whole [63]. For further classifying non-functional requirements, Sommerville [63] differentiates between product requirements, organizational requirements, and external requirements. Product requirements target the system or its components and, e.g., address the system's efficiency and dependability. Organizational requirements, among others, address the process of how the system is engineered respectively used in practice. External requirements comprise those requirements that are brought to the system from outside of the organization or the product. This especially includes legislative and ethical requirements. In this paper, we focus on eliciting the product requirements and the external requirements that an (battery) energy storage solution—as form—must satisfy in order to fit with a scenario—as context—in which energy needs to be stored and provided (Fig. 2).

We argue that an energy storage *solution* consists of two components. First, the battery pack, modules, or cells retrieved from an EV (together with other components) constitute the battery energy storage *system*. Second, services for ensuring the proper operation must accompany the battery energy storage system along its lifecycle, including logistics, assembly, and maintenance [6,59]. Importantly, both components must match the requirements of the second-life application scenario in order to provide value for customers. As a design-oriented field, Green IS research needs to propose IT artifacts that support identifying or developing fitting ensembles of second-life application scenarios and battery energy storage solutions.

3 Research method

Due to the complexity, immaturity, and innovativeness of the field, we performed an exploratory multi-method study for discovering and evaluating requirement metrics and categories for repurposing used EVBs. First, we developed three theoretical propositions to guide our research based on literature on requirements engineering and EVBs. Second, we conducted a Delphi study with battery experts to identify and rank requirement metrics and categories of second-life application scenarios. Third, we analyzed field data from an early proof-of-concept project in which cells from used EVBs were repurposed as a stationary battery energy storage system in order to verify the applicability of the requirement metrics as well as provide insights into a real-world case.

3.1 Theoretical propositions

While literature on repurposing used EVBs is scarce, our observations suggest that functional and non-functional

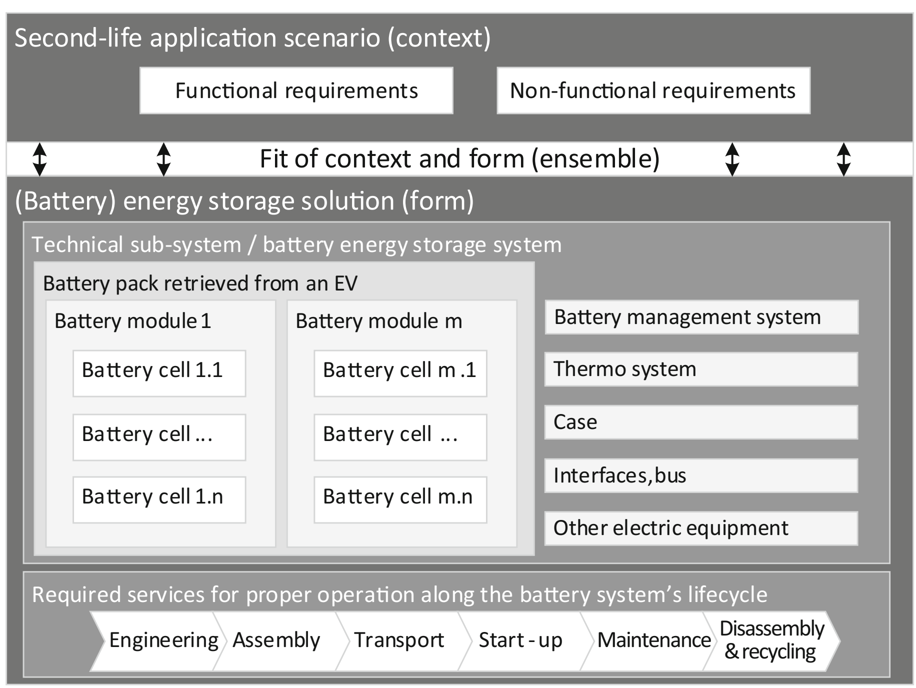

Fig. 2 Ensembles of second-life application scenarios and energy storage solutions for deciding on repurposing of EVBs

requirements govern the fit of a scenario as the context with an energy storage solution as a form, as described in Sect. 2.

Proposition 1 *The implementation of a battery energy storage solution in a second-life application scenario (ensemble) requires the fulfillment of functional and non-functional requirements of this scenario (context) by the battery energy storage solution (form). While functional requirements towards the solution (e.g., the general requirement of storing and providing electric energy or the proper operation) can be assumed to be the same among all second-life application scenarios, non-functional requirements refer to the details in each individual scenario (i.e., the meaning of "proper" in the according context).*

Additionally, the scenario's non-functional requirements towards the battery system are pivotal for the technical fit between scenario and battery. If a crucial parameter, such as the voltage of the battery system, does not meet the voltage requirement of the scenario, the according battery does not match to the scenario.

Proposition 2 *Non-functional requirements of a scenario (context) towards the battery energy storage system are more important for determining the fit or misfit of an energy storage solution (form) than are requirements towards the energy storage solution as a whole.*

Apart from the requirement categories and metrics that refer to a general scenario, *any single context* might result in a special set of non-functional requirements in two ways. First, each requirement metric becomes instantiated with a concrete parameter (e.g., "battery capacity" is instantiated with the value "40 Ah"). Second, additional requirement categories and metrics might emerge, whereas other metrics might be irrelevant. Therefore, we assume that it is necessary to compare the general set of requirement categories and metrics to field data from real-life cases.

Proposition 3 *In each individual context, non-functional requirements may be instantiated in a particular way and additional categories and metrics might emerge or be discarded.*

3.2 Delphi study

A Delphi study is "[…] a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem" [65]. As a tool for expert problem solving, the Delphi method is widely accepted in IS research [66]. Major areas of application for the method are, amongst others, forecasting or the identification and prioritization through a ranking in order to reach a group consensus on the relative importance of issues [67].

Our Delphi study was preceded by a literature search on current descriptions of second-life application scenarios for EVBs in research.[1] We consolidated the findings to a categorized list of metrics that was discussed in a workshop with seven battery experts. In a first qualitative round, we asked the experts to propose additional categories and metrics or to delete redundant ones from the list. In a second quantitative round the experts rated the items' importance. The result was a list of requirement categories and metrics that formed the starting point for the Delphi study.

The Delphi study itself consisted of two rounds. For the first round, we invited a panel of 68 battery experts from the German-speaking area that deal with battery systems or the topic of repurposing batteries in research or in their day-to-day business as providers of professional energy storage solutions. The experts were asked to rate the relevance of 45 metrics (relevant, not relevant, not sure) and of the according categories (five-point Likert scale, one not relevant to five very relevant) [68] for two different cases: first, as a basis for describing the general relevance of the metric or category for characterizing stationary, semi-stationary or mobile second-life application scenarios (henceforth called *generic*). Second, for the specific stationary scenario of employing the used battery as an energy storage solution in a smart home for the purpose of *residential load following* as used in the real-world case of the Efficiency House Plus in Berlin. Residential load following is a strategy intending to maximize the utilization of residentially generated energy (e.g., by on-site PV panels or a wind engine) by storing excess energy in a stationary energy storage [29,40,51]. The stored energy surplus can be used in times of insufficient energy production.

Overall, we received fully completed surveys from 20 experts. In line with the concept of a group decision-making process that is supported by the Delphi study we then aggregated the results and passed them back to the 20 experts. In the second round we asked the participants again to rate the relevance of the metrics (relevant, not relevant, not sure) and, this time, to explicitly rank the categories according to their importance for both cases. From the 20 participants of the first round 15 also responded to the second round. Because of the high bounce rate and stable answers for most metrics, we concluded the study after these two rounds. The resulting information can be used to prioritize and focus the categories in later applications for research and practice (e.g., for creating questionnaires or IT artifacts).

[1] Searches were conducted on Google Scholar and Scopus with the term: *("electric vehicle battery" OR "EVB") AND ("second-life" OR "repurposing" OR "further use" OR "second use" OR "re-use" OR "reuse").*

3.3 Case study: "EfficiencyHouse Plus"

A case study is "[…] a research strategy that examines, through the use of a variety of data sources, a phenomenon in its naturalistic context, with the purpose of 'confronting' theory with the empirical world" [69]. According to Yin [70], a case study is especially useful in situations in which (1) the main research questions are "how" or "why" questions; (2) a researcher has little or no control over behavioral events; and (3) the focus of the study is to research a contemporary phenomenon in its real life context [70]. We performed a positivist case study on a single-case with multiple (embedded) units of analysis, guided by the three theoretical propositions reported above.

The EfficiencyHouse Plus is one of the earliest proof-of-concept projects for repurposing used EVBs as a stationary battery energy storage system. Thus, it represents a revelatory case that warrants a single case study [70]. The multiple units of analysis, embedded in the single case, are the organizations and individuals that directly participated in the project in Berlin, Germany. The project's primary objective was to create a design for energy-efficient and resource-conserving living and transportation [71]. A secondary objective was to test if used EVBs can be repurposed as stationary energy storage systems. To test the facility in everyday life, a family of four moved in for the first trial period from March 2012 to August 2013. For this period, extensive secondary data was available for us to analyze. In the house, green energy was provided by a PV system. A surplus of power could be stored in a 40 kWh battery-system to be retrieved at times with high energy production or low demand [71]. Additionally, EVs could be recharged with that surplus energy.

For this case study we reviewed whitepapers and conducted interviews with the provider of the energy storage solution and with the project principal. Both interviews were tape-recorded and transcribed. Based on the transcripts, we performed open coding to identify which functional and non-functional requirements characterized the repurposing of the battery energy storage system. Apart from the requirements themselves, we collected the values that instantiated the requirements with data from the EfficiencyHouse Plus. In this way, the insights derived from the Delphi study were triangulated and instantiated with the evidence we identified in the case study.

4 Results and discussion

4.1 Finding 1: Prioritized requirement categories and metrics

In line with Proposition 1, we started our study with the assumption that a second-life application scenario is characterized by functional and non-functional requirements. According to Sommerville functional requirements "[…] describe what the system should do […]" [63], while non-functional requirements add constraints on the functions of the system [63].

We argue that the main purpose of every battery energy storage solution is to supply electric current (technical sub-system) and to ensure the proper operation (service sub-system). These general functional requirements on the technical sub-system and the service sub-system draw further functional requirements, like the charging capability, the protection against environmental influences (both technical), as well as the start-up and maintenance by an expert (both services). Our interviews revealed that the actual purpose of the system, which is to safely store and provide energy (functional requirements), do not differ pivotally between the system's first life in the car and the system's second life. What differs is the application-specific shaping of these functional requirements (e.g., required current, capacity, temperature range, or availability of the maintenance service), which are represented by non-functional requirements. Consequently, for finding a fit of second-life application scenario (context) and battery energy storage solution (form) that ensures the ensemble's operability, the non-functional requirements are crucial and are therefore in the focus of the further analysis.[2]

We built on the classification of Sommerville [63] to identify 11 categories and 45 metrics for describing non-functional requirements of energy storage solutions. We structured the requirements according to the components of the energy storage solution (Fig. 3). While requirements in the categories 'adequacy', 'space and weight', and 'durability' are directly related to the *battery system*, 'reliability', 'usability', 'economic feasibility', and 'safety and security' can be traced back to the *energy storage solution* as a whole. According to Sommerville [63], so-called *external requirements* refer to the properties of the entire product, and thus, in the present case, the entire energy storage solution.

In the expert workshop that preceded the Delphi study, several metrics and criteria were removed from the initial list. In these cases, the experts either agreed that most batteries from EVs are too similar in their characteristics (e.g., *charge*

[2] One can argue that besides the objective of ensuring the system's operability the ensemble of form and context is also affected by further objectives (e.g., ecological or social). From these objectives new scenario-specific functional requirements may arise that can be addressed by additional hardware components or value added services. Examples are the implementation of an energy load manager that allows to schedule and activate flexible electric loads (e.g., of dish washers or washing machines) to optimally use a battery's capacity and to reduce the amount of energy obtained from the public grid. However, these aspects require a more decent elaboration and are not in the focus of this work.

Fig. 3 Relevance of non-functional requirement metrics according to our Delphi study

			Stationary		Generic	
			Round 2	Round 1	Round 2	Round 1
Requirements on the battery system	Adequacy	Min., nominal and max. voltage [V]	(87/13/0)	(80/20/0)	(80/0/20)	(90/10/0)
		Capacity [Ah or kWh]	(93/7/0)	(95/0/5)	(100/0/0)	(95/0/5)
		Required power/peak power for time [W or VA (for min)]	(67/27/7)	(85/10/5)	(87/13/0)	(85/10/5)
		Required charging current [C]	(47/53/0)	(55/35/10)	(80/20/0)	(75/15/10)
		Required discharging current [C]	(40/47/13)	(55/35/10)	(67/20/13)	(80/10/10)
		Mean depth of discharge [%]	(73/27/0)	(70/25/5)	(87/13/0)	(75/15/10)
	Space and weight	Maximum length, height, width [cm, cm, cm]	(13/87/0)	(55/40/5)	(87/13/0)	(80/15/5)
		Maximum volume [l]	(13/87/0)	(30/65/5)	(80/20/0)	(60/25/15)
		Maximum mass [kg]	(7/87/7)	(30/70/0)	(80/20/0)	(65/30/5)
		Acceptable celltype (cylindric, prismatic, pouch)	(13/80/7)	(10/75/15)	(13/73/13)	(20/60/20)
	Durability	Expected cycle life until end of life [#full cycles]	(87/13/0)	(90/10/0)	(93/7/0)	(95/5/0)
		Expected energy throughput until end of life [Wh]	(93/7/0)	(90/5/5)	(87/13/0)	(90/5/5)
		Mean up time per day [min]	(47/47/7)	(60/25/15)	(40/53/7)	(70/25/5)
		Operating temperature (range) [°C]	(47/53/0)	(50/40/10)	(87/13/0)	(75/15/10)
		Derating factor [%]	(80/0/20)	(40/40/20)	(27/20/53)	(45/10/45)
Requirements on the energy storage solution	Reliability	Tolerable mean operating time between failures/outages [d]	(60/33/7)	(55/30/15)	(73/27/0)	(60/30/10)
		Tolerable mean time to restoration [min]	(87/13/0)	(75/20/5)	(87/13/0)	(80/15/5)
		Tolerable failures/outages in time [#in hours]	(67/27/7)	(50/25/25)	(73/27/0)	(70/25/5)
		Tolerable mean operating time to first failure [d]	(60/20/20)	(55/20/25)	(53/27/20)	(60/20/20)
		Tolerable self-discharge rate (e.g., per month at room temp.) [%]	(47/47/7)	(45/45/10)	(60/33/7)	(65/35/0)
	Usability	Compatibility to technical interfaces (e.g., CAN, USB)	(87/7/7)	(80/20/0)	(87/7/7)	(80/15/5)
		Required main user interface (e.g., GUI, terminal)	(67/20/13)	(60/25/15)	(67/27/7)	(60/30/10)
		Additionally required electric equipment	(53/27/20)	(45/35/20)	(73/13/13)	(55/25/20)
		Latest acceptable delivery date [yyyymmdd]	(33/20/47)	(30/15/55)	(33/20/47)	(50/5/45)
	Economic feasibility	Willingness to pay [€]	(100/0/0)	(100/0/0)	(100/0/0)	(100/0/0)
		Expected lifecycle costs [€]	(100/0/0)	(90/0/10)	(100/0/0)	(95/0/5)
		Lifecycle costs of rival energy solution [€]	(100/0/0)	(85/10/5)	(100/0/0)	(95/0/5)
	Security & safety	Security of the system (e.g., access options and rights)	(67/27/7)	(55/30/15)	(73/20/7)	(55/25/20)
		Safety	(93/7/0)	(85/15/0)	(93/7/0)	(85/15/0)
External requirements	Regulatory requirem.	Required security certificates [reference numbers]	(33/27/40)	(50/25/25)	(47/13/40)	(45/20/35)
		Required safety certificates [reference numbers]	(80/0/20)	(75/10/15)	(80/0/20)	(75/5/20)
	Legal requirem.	Warranty	(100/0/0)	(90/0/10)	(100/0/0)	(90/0/10)
		Product liability	(100/0/0)	(95/0/5)	(100/0/0)	(95/0/5)
		Legal access protection	(67/20/13)	(60/20/20)	(73/20/7)	(70/5/25)
		Legal safety	(93/7/0)	(89/0/11)	(93/7/0)	(90/0/10)
	Ethical requirem.	Privacy	(53/27/20)	(55/30/15)	(60/13/27)	(60/10/30)
		Required green energy certificates [reference numbers]	(67/0/33)	(55/20/25)	(67/0/33)	(50/20/30)

Relevance: 100% ≥ x > 75% 75% ≥ x > 60% 60% ≥ x > 40% 40% ≥ x > 25% 25% ≥ x
(relevant/not relevant/uncertain)

efficiency, time to power-up, operating elevation, and relative humidity, and detailed safety requirements), the metrics can be calculated on the basis of other metrics (e.g., *volumetric and gravimetric power and energy density*), and that mixing different battery types in a new energy storage solution is not reasonable at all, so that the metric does not need to be explicated (*cell chemistry*). In the Delphi study, the panelists checked the completeness, accuracy, and relevance of the proposed metrics and were invited to suggest new metrics.

The results of the Delphi study (Figs. 3, 4) reveal that for most items the ratings for the generic scenario and the specific case of residential load following in a stationary scenario are similar. Metrics such as the voltage, capacity (adequacy), cycle life, expected energy throughput (durability), the willingness to pay, expected lifecycle costs (economic feasibility), or the safety mechanisms, as well as product warranty, liability, and legally prescribed safety mechanisms (legal requirements), were rated as highly relevant (>75 % approval) for both cases. In contrast, significant differences can be observed for all metrics in the category space and weight, for the operating temperature, for the charging and discharging current and for the additionally required electric equipment. Mobile (e.g., scooter, golf car) or semi-stationary (e.g., power for stage equipment or construction sites) applications impose limitations with respect to size, volume, and weight because of restrictions, e.g., in the shell sizes or allowed overall transportable weight. These limitations were found to be less relevant in stationary scenarios. Likewise,

Fig. 4 Relevance of additional non-functional requirement metrics for residential load following

			Stationary	
			Round 2	Round 1
Spec. req. res. load f.	Adequacy	Open circuit/peak performance voltage of power source [V]	(73/13/13)	(65/20/15)
		Nominal power of power source [Wp, kWp or W, kW]	(87/7/7)	(95/0/5)
		Maximum output of power source per year [Wh or kWh]	(73/20/7)	(65/20/15)
		Average output of power source per day [Wh or kWh]	(87/7/7)	(85/5/10)
		Number of hours with full load of power source per year [#]	(73/13/13)	(68/26/5)
	Economic feasibility	Costs of purchased electricity from grid [€]	(93/0/7)	(75/10/15)
		Compensation for green electricity fed into the grid [€]	(80/20/0)	(75/15/10)
		Compensation for stored electricity fed into the grid [€]	(87/13/0)	(85/5/10)

Relevance: 100% ≥ x > 75% 75% ≥ x > 60% 60% ≥ x > 40% 40% ≥ x > 25%
(relevant/not relevant/uncertain)

Table 1 Ranking of requirement categories; 2nd round (median, mode), 1st round [Likert 5, strongly relevant (left) to not relevant (right)]

Category	Rank stationary		Rank generic	
	Round 2	Round 1	Round 2	Round 1
Safety and security	1 (1/1)	2 (70/20/10/0/0)	1 (1/1)	1 (75/15/10/0/0)
Adequacy	2 (2/1)	1 (85/15/0/0/0)	3 (4/2)	3 (55/25/20/0/0)
Durability	3 (3/3)	3 (45/50/5/0/0)	5 (5/5)	5 (50/40/5/0/5)
Reliability	4 (4/3)	4 (60/20/10/10/0)	4 (4/6)	4 (45/45/10/0/0)
Economic feasibility	5 (5/2)	5 (40/35/25/0/0)	2 (3/2)	2 (55/35/10/0/0)
Usability	6 (6/6)	7 (40/30/20/10/0)	6 (6/6)	6 (40/30/25/5/0)
Residential load following	7 (7/7)	6 (50/15/30/5/0)	n.a.	n.a.
Regulatory requirements	8 (8/8)	9 (20/30/40/10/0)	8 (8/8)	8 (10/35/40/15/0)
Legal requirements	9 (8/9)	8 (30/35/35/0/0)	7 (7/7)	7 (15/55/25/5/0)
Ethical requirements	10 (10/10)	10 (10/30/20/20/20)	10 (10/10)	10 (5/20/35/15/25)
Space and weight	11 (11/11)	11 (5/10/20/35/30)	9 (9/9)	9 (10/35/35/15/5)

the operating temperature can be more easily controlled in a stationary case. Finally, in contrast to a mobile or semi-stationary scenario, in which the battery is the sole power source, the charging and discharging currents, as well as the peak power are less relevant in a stationary case with better projectable demands, a sophisticated power electronics environment, and an option to fall back to the conventional energy grid. Only the *acceptable cell type*, the *latest acceptable delivery date* as well as *security certificates* were identified to be rather irrelevant criteria.

Finally, the specific criteria for residential load following (Fig. 4) all received a medium or high acceptance rate and consequently form an additional set of requirements for these stationary scenarios.

The results of the rating and ranking of the requirement categories (Table 1) are sorted according to the resulting ranks of the stationary scenario.

In terms of Proposition 2, the results confirm that the requirement category adequacy and its metrics are highly relevant for repurposing an EVB. However, safety and security, economic feasibility, reliability, and durability are comparably important categories that contain metrics that must be met by the entire energy storage solution if an EVB should be repurposed successfully.

4.2 Finding 2: Instantiated requirement metrics at the EfficiencyHouse Plus

In the case study, we analyzed which requirements—identified in the Delphi study—were actually found to be relevant in the EfficiencyHouse Plus case (Fig. 5). The data showed that the house is equipped with two types of PV panels [71,72]. The flat roof of the building contains about 98 m^2 of monocrystalline PV modules, producing about 11,500 kWh of energy per year, while the façade's 73 m^2 thin film PV modules produce about 5000 kWh per year.

In Germany, an average four-person household consumes about 5000 kWh of electric energy per year [73]. Since the EfficiencyHouse Plus included EVs, pedelecs, and means for fostering the public image of the research project (e.g., implemented outdoor lighting and additional monitors), the house required 13,000 kWh of electricity per year (7000 kWh for the house, 6000 kWh for EVs).

The battery energy storage system was configured to almost fully store the energy required on an average day. These requirements resulted in a battery system with about 42 kWh/1000 Ah of rated capacitance and about 40 kWh (834 Ah) of useable capacitance. The battery modules were retrieved from BMW Mini e full-electric vehicles and

			Observations between March 2012 to May 2013
Requirements on the battery system	Adequacy	Final discharging voltage	42 V; nominal voltage: 51.8 V; charging voltage: 56 V
		Useable capacitance	834 Ah / 40 kWh
		Max. peak power for time	6,500 W for 30 min.; 7,200 W for 5 min.; 8,400 W for 1 min.
		Max. charging current	<360 A // Max. discharging current: <500 A
		Mean depth of discharge	~ 40% (max. 100%, May to September); ~ 25 % (max. ~ 60%, September to November); ~ 0.2 % (max. ~ 15%, November to March); ~ 15 % (max. ~ 60%, March to May)
		Nominal power of power source	14.1 kW_p (roof); 8 kW_p (façade)
		Maximum output of power source p.a.	~ 16,500 kWh (expected); ~ 13,300 kWh (March to February)
		Average output of power source p.d.	~ 45 kWh (expected); ~ 36 kWh (March to February)
	Space and weight	Length, height, width	80 cm, 160 cm, 80 cm (incl. switching cabinets)
		Weight	991 kg (~ 600 kg for the battery)
	Durability	Number of cycles (May to May)	99.7 (thereof 76.1 full cycles, charging); 77.7 (thereof 53.9 full cycles, discharging)
		Energy throughput (May to May)	~ 4,400 kWh (charging); ~ 3,350 kWh (discharging); ~ 1,200 kWh climate control; ~ 850 kWh ventilation; ~ 950 kWh (loss due to electric components, self-discharge, efficiency)
		Operating temperature range	-3 °C to +45 °C (charging, storage); -5 °C to +45 °C (discharging); controlled to lie between 10 °C and 30 °C
Req. on the energy storage solution	Reliability	Mean operating time between failures	~ 1 month
		Failures/outages in time	7 incidents between May 2012 and May 2013
		Operating time to first failure	~ 1.5 months
	Usability	Supported technical interfaces	CAN bus; Ethernet (via adapter from CAN bus)
		Supported main user interface	Status monitor; data access via ethernet
		Additionally required electric equipm.	Amongst others a.c. converter; battery management system, programmable logic controller, switch cabinet, heater, cooler, fans, relays, lightning protection, main contactor, ground fault circuit interrupter
	Economic feasibility	Initial cost	~ 170,000 € (incl. analyzing of cells and development of BMS)
		Initial cost of rival energy solution	47,000 € to 75,000 € (for ~ 30 kWh useable capacitance with new lithium ion cells)

Fig. 5 Data table for requirements in second-life application scenarios, with data from the analyzed case

had about 80 % of the modules' original energy storage capacity.

4.3 Finding 3: Special requirements for residential load following

In line with Proposition 3, the evidence we obtained on the EfficiencyHouse Plus indicates that the requirements in this case detailed the categories and metrics identified in our studies, but also differed to some extent (Table 2). The data suggest that adequacy and economic feasibility were the two distinctive non-functional requirements. While reliability itself was not viewed as a crucial requirement, it is important indirectly, since unexpected service events severely impede the economic feasibility of the energy storage solution. Space and weight, durability, usability, and legal requirements were found to be general constraints for the whole solution, but were not specific for manufacturing the battery system itself.

Functional requirements: In the case, a new battery management system (BMS) needed to be designed particularly for this application scenario, resulting in high costs and in an inability to build on a consistent and well-tested energy storage solution. These costs would have rendered the project unsuccessful under realistic market conditions.

Adequacy: While the project itself was focused on providing an energy efficient building, the energy storage system was designed to fit the technical specifications of the solar modules:

> *"We [designed the battery system] to fit the properties of the photovoltaic system one-on-one […]. We designed it to store the amount of energy needed in the house for one complete day, and added some additional capacity, since we had additional battery modules available" (Principal).*

The battery's capacity was too large for the power provided by the PV panels, even considering that sunshine in the

Table 2 Overview of the case's implications on the identified requirement categories

Category	Implications derived from the EfficiencyHouse Plus case
Functional req.	A battery energy storage system must be kept intact when applied in a second-life application scenario, since the costs of designing, adding, or exchanging components are prohibitively high
Adequacy	Technical adequacy is the most important requirement to make the battery working with a PV system. However, the battery's capacity was too large in this case
Space and weight	Space and weight are general and implicit constraints for manufacturing a battery energy storage system
Durability	Using EVBs as a stationary battery energy storage system in a house decreases the durability of the battery very slowly. Nevertheless, durability is a constraint for manufacturing a battery energy storage system
Reliability	Stationary battery energy storage systems must be recharged to avoid deep discharges. 100 % availability is not necessary if a house is connected to the regular energy grid
	However, the battery must be reliable and easy to maintain for economic reasons, since resolving disruptive service events turned out to be very expensive
Economic feasibility	The condition of the EVB must be estimated without testing each cell separately. Under market conditions, economic aspects must be assessed thoroughly

observed period was below average. Most of the time, solar energy inadequately charged the battery and, moreover, in winter months a battery with a capacity of 6.5 kWh would have been sufficient:

> *"Whereas the capacity was adequate during the summer, it was too big during the winter" (Provider).*

Space and weight: Space and weight restrictions were considered as minor constraints, since the battery was placed in front of the building for safety reasons:

> *"Space and weight were of secondary importance. The cabinet in which the EVBs were installed was the only size constraint" (Provider).*

Durability: The usable corridor for charging and discharging the battery was set to 20–80 % in order to protect the battery from overcharging and deep discharging. While the battery system was dimensioned to be larger than necessary, the experts believe that the cells did not age significantly due to the less demanding requirements of storing energy in a stationary scenario (as compared to an EV):

> *"In a car, you suddenly need 100 kW of energy, whereas in a house the battery is charged and discharged much more slowly. […] After having used the battery cells for four years, I do not see that the battery cells have deteriorated in any way. But we did not analyze the cells in detail" (Principal).*

Reliability: Due to the proof-of-concept properties of the project, reliability requirements could not be specified in advance. However, data from the operations stage proves that the battery was insufficiently supplied with energy some of the time. Moreover, the insufficient energy supply resulted in several deep discharges that rendered the battery inoperative and even destroyed some of the battery cells:

> *"[Unexpected] deep discharging turned out to be a major problem. What we did not know was that the inverter we used consumed energy from the battery pack itself. In the operations stage, they went into a stand-by mode that consumed energy from the cells, leading to a deep discharge until the BMS intervened and shut down the battery. After that we knew that we needed to trace the battery system's state of charge and recharge it with energy from the grid, if necessary" (Principal).*

From a functional point of view, the reliability of the battery system was not considered as a crucial requirement, since the house was connected to the regular energy grid:

> *"100 % up-time of the battery system is not required in a house and it would cause immense additional costs to achieve this level of reliability. If the battery system is down for some days, you can still use energy from the regular grid in the house" (Principal).*

However, the project revealed that reliability is crucial from an economic perspective, since maintaining the battery system would cause costs that might let a project fail under market conditions:

"We had downtimes longer than a few days or even weeks, since we did not know what exactly went wrong. […] Expenses for maintenance would have jeopardized the entire project" (Principal).

Usability was not considered as a specific requirement. However, the system was required to provide Ethernet access with an uplink to the web for status monitoring.

Economic feasibility was considered broadly as a constraint. While it was not intended to maximize economic profit, the project needed to comply with the financial resources provided:

"The battery was designed for functionality, not for optimizing its economic value. I estimate the costs of repurposing the battery to some 170,000 €, since we needed to design a new BMS" (Principal).

Safety/security: The battery was put into a case successfully protecting it from unauthorized access.

Legal, regulatory, and ethical requirements: For safety reasons, the battery was positioned outside the building. The legal requirements included approvals to utilize the battery, and providing signs for fire fighters. Ethical considerations were not considered explicitly as requirements.

5 Conclusion and outlook

In our exploratory multi-method study, we identified and systematized the requirement categories and metrics that govern the fit of an energy storage solution (as form) and a second-life application scenario (as context). We offer two contributions. First, we proposed a prioritized set of requirement categories and metrics that govern the fit or misfit between an energy storage solution and the context in which it is applied. IT artifacts to assist human users in repurposing EVBs must, therefore, be designed to instantiate these criteria for different second-life application scenarios, such that the scenarios' fit with an energy storage solution can be elicited. Second, we provided an according instantiation for the revelatory *EfficiencyHouse Plus* case. Thus, we detailed the list of requirements for stationary applications and offer a data table that allows other researchers to describe requirements in their own second-life application scenarios. By reviewing the requirements and other data from the analyzed case, we provide a detailed description of a stationary context in which modules of EVBs were successfully repurposed. While the interviews revealed that repurposing EVBs as stationary energy storage systems is still somewhat immature and costly, IS might help to identify ensembles of energy storage solutions and second-life application scenarios. As a design-oriented research field, Green IS research has to play a vital role towards that end.

In line with this claim, our results provide justificatory knowledge [21,22] that informs and constrains the design of IT artifacts for repurposing EVBs. For instance, this knowledge can be valuable for designing a decision support system (DSS) for identifying the best EVB for a second-life application scenario, based on minimizing the battery's technical misfit with the context. Such a DSS would depend on characterizing different scenarios with the requirement categories and metrics proposed in this paper.

Limitations of our research refer to the obvious impossibility of specifying a finite set of requirements for any context, as identified in seminal research [60]. In addition, the requirement categories and metrics identified in the revelatory case might not be fully representative for other stationary scenarios and might be affected by the particular environment (e.g., country-specific legislation). While case studies are inherently limited to abstract generalizability [70], we propose to validate our results in other repurposing scenarios, as soon as additional projects will be conducted. Finally, the present paper mainly focusses on the technical fit of context and form, whereas other objectives (e.g. ecological or social objectives) are not taken into account. Additional functional and non-functional requirements could target add-on functionalities of an energy storage solution that could be fulfilled by additional hardware components (e.g., web access of battery storage system) or value-added services (e.g., remote monitoring and consultancy about optimal use of energy storage). Considering these aspects might help providers to define value-added business models for repurposed EVBs that can compete with new battery energy storage systems.

Acknowledgements This article was written in the research project 'EOL-IS' (End-of-Life Solutions for Electric Vehicle Batteries—Development of Product Service Systems and Information Systems for Decision Support; funding label: 01FE13023) in the context of the funding program "Service Innovations for Electric Mobility" granted by the German Federal Ministry of Education and Research (BMBF). We thank the project management agency National Aeronautics and Space Research Centre of the Federal Republic of Germany (DLR) for their support.

References

1. European Commission (2015) Road transport: reducing CO_2 emissions from vehicles. http://ec.europa.eu/clima/policies/transport/vehicles/index_en.htm. Accessed 27 Apr 2015
2. European Commission (2011) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions—a roadmap for moving to a competitive low carbon economy in 2050. Change. doi:10.1002/jsc.572
3. International Energy Agency (2012) Energy technology perspectives 2012—pathways to a clean energy system. doi:10.1787/energy_tech-2012-en

4. King C, Griggs W, Wirth F, Quinn K, Shorten R (2014) Alleviating a form of electric vehicle range anxiety through on-demand vehicle access. Int J Control 88:717–728
5. Nationale Plattform Elektromobilität (2014) Fortschrittsbericht 2014—Bilanz der Marktvorbereitung, Berlin
6. Beverungen D, Klör B, Bräuer S, Monhof M (2015) Will they die another day? A decision support perspective on reusing electric vehicle batteries. In: Proceedings of twenty-third European conference on information systems (ECIS 2015)
7. Nykvist B, Nilsson M (2015) Rapidly falling costs of battery packs for electric vehicles. Nat Clim Change 5:329–332
8. Ahmadi L, Fowler M, Young SB, Fraser RA, Gaffney B, Walker SB (2014) Energy efficiency of Li-ion battery packs re-used in stationary power applications. Sustain Energy Technol Assess 8:9–17. doi:10.1016/j.seta.2014.06.006
9. Burke A (2009) Performance, charging and second use considerations for lithium batteries for plug-in electric vehicles. Research Report UCD-ITS-RR-09-17. Institute of TransportationStudies, University of California, Davis
10. Elkind EN (2014) Reuse and repower—how to save money and clean the grid with second-life electric vehicle batteries. UCLA School of Law, Technical Report, Los Angeles, California
11. Neubauer JS, Pesaran A, Williams B, Ferry M, Eyer J (2012) A techno-economic analysis of PEV battery second use: repurposed-battery selling price and commercial and industrial end-user value. SAE International, SAE Technical Papers, Detroit, MI
12. Colthorpe A (2015) Bosch, BMW, Vattenfall resurrect EV batteries for "second life" as large-scale energy storage. In: StoragePVTech. http://storage.pv-tech.org/news/bosch-bmw-vattenfall-resurrect-more-ev-batteries-for-second-life-as-large-s. Accessed 4 May 2015
13. Howard B (2013) GM turns old Chevy Volt battery into a whole-house UPS. In: ExtremeTech. http://www.extremetech.com/extreme/155589-gm-turns-your-old-chevy-volt-battery-into-a-whole-house-ups. Accessed 4 May 2015
14. Reportlinker (2014) Second-life batteries: from PEVs to stationary applications. http://www.prnewswire.com/news-releases/second-life-batteries-from-pevs-to-stationary-applications-242205851.html. Accessed 27 Apr 2015
15. EV World (2011) Lithium battery recycling exptected to reach $2B by 2022. http://evworld.com/news.cfm?newsid=25315. Accessed 26 Apr 2015
16. Aziz M, Oda T, Morihara A, Murakami T, Momose N (2014) Utilization of EVs and their used batteries in factory load leveling. Innov Smart Grid Technol Conf (ISGT), 2014 IEEE PES 1–5
17. Gabriel R (2013) Informationssystem @ www.enzyklopaedie-der-wirtschaftsinformatik.de. http://www.enzyklopaedie-der-wirtschaftsinformatik.de/lexikon/uebergreifendes/Kontext-und-Grundlagen/Informationssystem. Accessed 10 Jun 2016
18. Boudreau M-C, Chen AJ, Huber M (2007) Green IS?: building sustainable business practices. In: Inf Syst Glob Text Proj. pp 1–15
19. Watson RT, Boudreau M-C, Chen AJ (2010) Information systems and environmentally sustainable development: energy informatics and new directions for the IS community. MIS Q 34:23–38
20. Vom Brocke J, Watson RT, Dwyer C, Elliot S, Melville N (2013) Green information systems: directives for the IS discipline. Commun Assoc Inf Syst 33:509–520
21. Gregor S, Jones D (2007) The anatomy of a design theory. J Assoc Inf Syst 8:313–335
22. Gregor S, Hevner AR (2013) Positioning and presenting design science research for maximum impact. MIS Q 37:337–356
23. Ahmadi L, Young SB, Fowler M, Fraser RA, Achachlouei MA (2015) A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. Int J Life Cycle Assess 1–14. doi:10.1007/s11367-015-0959-7
24. Sathre R, Scown CD, Kavvada O, Hendrickson TP (2015) Energy and climate effects of second-life use of electric vehicle batteries in California through 2050. J Power Sources 288:82–91
25. Ahmadi L, Yip A, Fowler M, Young SB, Fraser RA (2014) Environmental feasibility of re-use of electric vehicle batteries. Sustain Energy Technol Assess 6:64–74
26. Neubauer JS, Wood E, Pesaran A (2015) A second life for electric vehicle batteries: answering questions on battery degradation and value. SAE Int J Mater Manuf 8:21–23
27. Narula CK, Martinez R, Onar O, Starke MR, Andrews G, Laboratory ORN (2011) Final report— economic analysis of deploying used batteries in power systems. Oak Ridge, Tennessee
28. Foster M, Isely P, Standridge CR, Hasan MM (2014) Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries. J Ind Eng Manag 7:698–715
29. Cready E, Lippert J, Pihl J, Weinstock I, Symons P, Jungst RG (2003) Technical and economic feasibility of applying used EV batteries in stationary applications—a study for the DOE energy storage systems program. Sandia National Laboratories, Technical Report, Albuquerque, New Mexico
30. Gohla-Neudecker B, Bowler M, Mohr S (2015) Battery 2nd life: leveraging the sustainability potential of EVs and renewable energy grid integration. In: Proceedings of the 2015 international conference on clean electrical power, pp 311–318
31. Walls JG, Widmeyer GR, El Sawy OA (1992) Building information system design theory for vigilant EIS. Inf Syst Res 3:36–59
32. Dao V, Langella I, Carbo J (2011) From green to sustainability: information technology and an integrated sustainability framework. J Strateg Inf Syst 20:63–79
33. World Commission on Environment and Development (1987) Report of the world commission on environment and development: our common future
34. Elkington J (2004) Entre the triple bottom line. In: Triple bottom line does it all add up, pp 1–16
35. Elkington J (1994) Towards the sustainable corporation: Win–Win–Win business strategies for sustainable development. Calif Manag Rev 36:90–100
36. Dyllick T, Hockerts K (2002) Beyond the business case for corporate sustainability. Bus Strateg Environ 11:130–141
37. Jenkin TA, Webster J, McShane L (2011) An agenda for 'Green' information technology and systems research. Inf Organ 21:17–40. doi:10.1016/j.infoandorg.2010.09.003
38. Arvind M, Melville NP, Watson RT (2013) Spurring impactful research on information systems for environmental sustainability. MIS Q 37:1265–1274
39. Kossahl J, Busse S, Kolbe LM (2012) The evolvement of energy informatics in the information systems community—a literature analysis and research agenda. ECIS 2012 Proc
40. Knowles MJ, Morris A (2014) Impact of second life electric vehicle batteries on the viability of renewable energy sources. Brit J Appl Sci Technol 4:152–167
41. Viswanathan VV, Kintner-Meyer M (2011) Second use of transportation batteries: maximizing the value of batteries for transportation and grid services. IEEE Trans Veh Technol 60:2963–2970
42. Bowler M (2014) Battery second use: a framework for evaluating the combination of two value chains. Doctoral Dissertation, Clemson University, Clemson, SC
43. Thierry M, Salomon M, Van Nunen J, Van Wassenhove L (1995) Strategic issues in product recovery management. Calif Manag Rev 37:114–135
44. Ramoni MO, Zhang H-C (2013) End-of-life (EOL) issues and options for electric vehicle batteries. Clean Technol Environ Policy 15:881–891

45. Strandridge CR, Corneal L (2014) Remanufacturing, repurposing, and recycling of post-vehicle-application lithium-ion batteries. Technical Report, San José State University
46. Williams B, Lipman T (2011) Analysis of the combined vehicle—use value of lithium-ion plug-in-vehicle propulsion batteries—Task 3, second life applications and value of "Traction" lithium batteries. University of California, Berkley—Transportation Sustainability Research Center, Technical Report, Berkley, California
47. Price B, Dietz E, Richardson J (2012) Life cycle costs of electric and hybrid electric vehicle batteries and end-of-life uses. In: IEEE international electro/information technology conference, Indianapolis, IN, pp 1–7
48. Stan A-I, Swierczynski M, Stroe D-I, Teodorescu R, Andreasen SJ (2014) Lithium ion battery chemistries from renewable energy storage to automotive and back-up power applications—an overview. In: 2014 international conference on optimization of electrical and electronic equipment, pp 713–720
49. Rittershausen J, McDonagh M (2011) Moving energy storage from concept to reality: Southern California Edison's approach to evaluating energy storage. Rosemead, California, USA
50. Denholm P, Ela E, Kirby B, Milligan M (2010) The role of energy storage with renewable electricity generation. National Renewable Energy Laboratory, Technical Report, Golden, Colorado
51. Prüggler W (2012) The impact of second life applications of electric vehicle batteries on customer's mobility cost. In: EnInnov2012-12. Symp. Energieinnovation—Altern. für die Energiezukunft Eur. Graz, Österreich, pp 1–22
52. Lacey G, Putrus G, Salim A (2013) The use of second life electric vehicle batteries for grid support. Eurocon 2013:1255–1261
53. Patten J, Srivastava S, Nola G, Christensen N (2011) Electric vehicle battery—wind energy storage system. IEEE Veh Power Propuls Conf 2011:1–3
54. Alimisis V, Hatziargyriou ND (2013) Evaluation of a hybrid power plant comprising used EV-batteries to complement wind power. IEEE Trans Sustain Energy 4:286–293
55. Siret C, Yazicioglu B, Tytgat J, et al (2014) Title of the study: high specific energy rechargeable batteries used as a main source of energy for mobile application—definition of scope, representative product and description of the model for the PEF screening study. Recharge—The European Association for Advanced Rechargeable Batteries (not specified)
56. BU-1201: hybrid electric vehicle—battery University. http://batteryuniversity.com/learn/article/hybrid_electric_vehicle. Accessed 3 May 2015
57. Recyclingportal.eu (2016) Possible second life for electric cars' batteries in refugee camps. http://recyclingportal.eu/Archive/22213. Accessed 29 Mar 2016
58. Genikomsakis KN, Ioakimidis CS, Murillo A, Trifonova A, Simic D (2013) A life cycle assessment of a Li-ion urban electric vehicle battery parameters settings for EVs in. In: EVS27 international battery, hybrid and fuel cell electric vehicle symposium, Barcelona, Spain, pp 1–11
59. Bräuer S (2016) They not only live once—towards product-service systems for repurposed electric vehicle batteries. In: Proceedings of Multikonferenz Wirtschaftsinformatik 2016
60. Alexander C (1964) Notes on the synthesis of form. Harvard University Press, Cambridge
61. International Organization For Standardization (2010) ISO/IEC/IEEE24765:2010 Systems and software engineering - Vocabulary
62. Bourque P, Fairley R (eds) (2014) Guide to the software engineering body of knowledge, Version 3.0. IEEE Computer Society
63. Sommerville I (2010) Software engineering, 9th ed. Pearson
64. Bass L, Clements P, Kazman R (2003) Software architecture in practice (SEI Series in Software Engineering), 2nd edn. Addison Wesley, Reading
65. Linstone HA, Turoff M (2002) The Delphi method—techniques and applications. Delphi Method Tech Appl:1–616
66. Okoli C, Pawlowski SD (2004) The Delphi method as a research tool: an example, design considerations and applications. Inf Manag 42:15–29
67. Schmidt RC (1997) Managing Delphi surveys using nonparametric statistical techniques. Decis Sci 28:763–774
68. Likert R (1932) A technique for the measurement of attitudes. Arch Psychol 22:55
69. Piekkari R, Welch C, Paavilainen E (2009) The case study as disciplinary convention. Organ Res Methods 12:567–589
70. Yin RK (2013) Case study research: design and methods (applied social research methods), 5th edn. Sage Publications Ltd., Thousand Oaks
71. Erhorn H, Bergmann A, Beckert M, Reiß J, Hegner HD (2013) Messtechnische und energetische Validierung des BMVBS-Effizienzhaus Plus in Berlin—Messperiode März 2012 bis Februar 2013. Bauphysik 35:162–171
72. Federal Ministry for the Environment Nature Conservation Building and Nuclear Safety (2014) Wege zum Effizienzhaus Plus. 52
73. EnergieAgentur.NRW (2011) Erhebung "Wo im Haushalt bleibt der Strom?" Düsseldorf

Daniel Beverungen is a Professor for Information Systems at the University of Paderborn, Germany. His main research interests comprise service science management and engineering, business process management, information modelling, and the socio-technical design of information systems. His work has been published in peer-reviewed academic journals and was presented at all major Information Systems conferences. He is a member of the editorial board for the journal Business & Information Systems Engineering and has been serving as a chair, associate editor, and reviewer for various academic conferences and journals.

Sebastian Bräuer holds a Master's Degree in Information Systems and is currently a research assistant and Ph.D. candidate at the Department of Information Systems at the University of Münster, Germany. He is mainly interested in the role of services as catalysts for new businesses, such as EVB second use. This especially includes research on service engineering, value networks, and product-service systems.

Florian Plenter holds a Master's Degree in Economics and is currently a research assistant and Ph.D. candidate at the Department of Information Systems at the University of Münster, Germany. His research interests cover energy economics, the Sharing Economy, and especially how services and information systems support new business models in the domain of electric vehicles.

Benjamin Klör is a research assistant and Ph.D. candidate at the University of Münster, Germany. He holds a Master of Science in Information Systems from the University of Duisburg-Essen, Germany. He also studied at the University of Zurich, Switzerland. His research interests encompass business intelligence, decision support systems, operations research, and software engineering. He has published his work at leading national and international conferences.

Markus Monhof holds a Master's Degree in Information Systems and is a research assistant and Ph.D. candidate at the Department of Information Systems at the University of Münster. His research interests include software engineering, business intelligence, and operations research. At the current point of time, he is working in the field of electric mobility.