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Data model for KPI-based sustainability assessment of battery production and remanufacturing scenarios

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Abstract

Though batteries are of central future importance for climate friendly technologies, they cause significant environmental and economic costs over their entire product life cycle. These must be quantified in sustainability assessments for holistic evaluation for first and second life scenarios. Due to ageing and remanufacturing, product life cycles of individual batteries can vary greatly so that existing generic assessment methods are unsuitable. Therefore, this paper presents a data model for KPI-based sustainability assessments for individual batteries. The requirements are deductively derived from general KPI requirements in manufacturing and the KPI structure as well as KPI systems for sustainability assessments in production, enablers for circular economy in electric vehicle battery life cycles and use cases of the battery production, remanufacturing, and second-use scenarios. The resulting structure for a KPI set considers the data quality requirements for reliable and transparent assessments. This paper contributes to viable and comparable sustainability assessments regarding individual product life cycles.

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Keywords: sustainability KPIs, data model, data quality, battery life cycle, sustainability insights, decision making

1. Introduction

The increasing demand for batteries for electric vehicles (EV) in combination with their complex and material-intensive production results in a shortage in battery materials. Hence efforts to minimize the loss of value of the EV batteries at the End of Life (EoL) are extensive. [1] In the last years numerous scenarios for 2nd use and 2nd life of EV batteries and suitable remanufacturing processes have been developed. To evaluate the different scenarios and enable the decision on 2nd life and 2nd use scenarios of these batteries, a trustworthy evaluation of their environmental footprint is needed [2]. This requires a data-based assessment including virgin production and remanufacturing as well as EoL impact evaluation of remanufacturing and recycling. [3]

Due to the various steps in battery (re-)manufacturing, multiple involved businesses, multiple use scenarios and differing use phases, a major challenge is data access [4]. Further challenges are the variance in batteries and tailored battery management systems as well as technology changes [5, 6]. These complex circumstances lead to several issues in data quality: data is scattered, evolving from different data sources, partly unavailable, not quantifiable in quality and trustworthiness. Additionally, data differs even for the same use scenario due to individual use phases, varying battery aging and life spans. [5]

Sustainability assessment therefore poses a challenge, since a common information level and a corresponding set of Key-Performance-Indicators (KPIs) for the transparent and comparable evaluation of different scenarios is not given.

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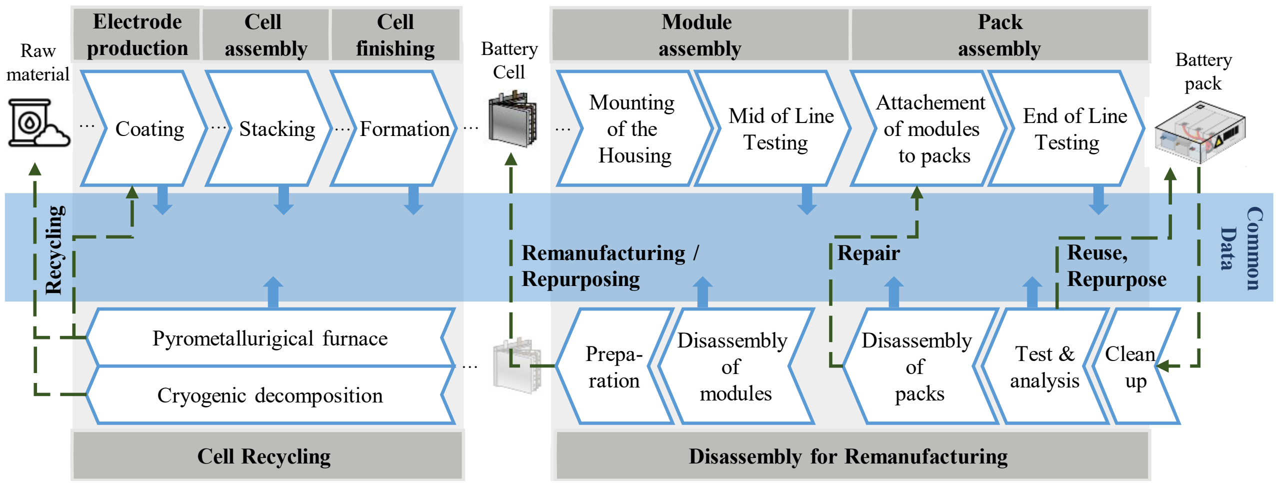

Fig. 1. Possible scenarios in the product life cycle of a battery: first life production to the remanufacturing for second use applications.

To evaluate different scenarios a consistent data basis across the complete life cycle and KPIs for the operationalization of R-strategies in battery production are needed. This paper aims to define the structure for KPIs for sustainability assessment in battery (re-)manufacturing including the data quality requirements as well as defining KPI categories specific to the volatile (re-)manufacturing and EoL scenarios of batteries. The scope of this paper is solely focussing the environmental dimension of sustainability assessments for (re-)manufacturing of EV batteries.

2. State of the art

In the following section the state of the art regarding battery (re-)manufacturing and enablers for 2nd use and circular economy (CE) as well as KPI sets for battery (re-)manufacturing are presented. Furthermore, requirements and structures of KPIs and proposed methods of establishing data quality in sustainability assessments are discussed.

2.1. Battery production – first life production and remanufacturing for second use scenarios

The generalized principles of a lithium-ion-battery production chain depict the scope of this paper (see Fig. 1). In the first step of battery production, raw materials are turned to electrode sheets. These are cut and assembled to battery cells. In the second part, multiple cells are assembled to modules. After module testing, they are assembled to battery packs before they must pass end of line testing. [7–9]

After the intended first life, there are several possible second life scenarios depending on the individual technical condition at the End of Life (EoL). Batteries can be reused in the same approach as in the first life (“second use”). [5] However, due to aging this is often not an option. With a suitable remanufacturing approach of cleaning, testing, and dissembling the battery packs, modules can be detached and fed back into production. Depending on the capabilities of the remanufacturing system, the disassembly depth can vary from module to cell level. [10] If the condition of the cells is not sufficient, batteries are recycled as a homogeneous mix or to the raw materials [11].

While those scenarios appear to interact into one flow system, reuse and remanufacturing procedures are still very uncommon. The condition variance of EoL batteries and fed back components results in volatility. Hence a key enabler is the infrastructure for flexible processing. [6] Additionally the evaluation of the batteries at the EoL and 2nd life decision making is essential to realize CE. [4, 6, 12] Therefore, a major obstacle is the (re-)use of data. For every process step in manufacturing, process and product data should be acquired and distributed throughout the supply chain to derive holistic cause-effect relationships and meaningful KPIs. [13] Hence a common data structure for KPIs including the batteries’ historic and material data are crucial for the decision paths and possible technical implications for remanufacturing. [10]

2.2. Structure and requirements for the KPI sets

KPI-based assessment is a widely used tool in business and reporting. Assessments enable optimisations and reportings while indicators operationalize those on the political, company and process level and to reflect, analyse and evaluate diverse cause-and-effect relationships [14, 15]. The structure and requirements for KPIs in manufacturing is described in the ISO 22400 [16]: This standard provides a set of twenty requirements for KPIs and a generalized KPI set for manufacturing companies. The structure definition is including content information – name, ID, description, scope, formula, unit of measure, range, and trend – and context information – timing, constraints, usage, audience, production methodology and effect model diagram. [16]

Despite the concreteness, this standard does not apply to the requirements arising from volatile processes due to the operationalization of R-scenarios. Additionally, the KPIs’ structure does not explicitly regard the aspects of data quality and Industry 4.0. [16] Yet, major changes arise within the production systems due to Industry 4.0. Hence JOPPEN ET AL. introduce “transparency” and “networking requiring functioning data management” as KPI requirements. [17]

2.3. Data quality in KPI-based environmental assessment

Section 2.2 depicted the structure and general requirements for KPI sets used in assessments. A holistic data quality model allows for a structured storage and evaluation of the data. Yet, in the common definition of KPIs data quality is not regarded as a quantifiable definition criterion but only included implicitly in the requirements such as "accuracy," "validity" and "accessibility." [6, 16, 18]

Data quality dimensions are addressed as an important role in the set-up and implementation of sustainability assessment [19–21] since the quality of the data being used strongly influences the results and their reliability [22]. For example, the DIN EN ISO 14040 approaches data quality by comparing data requirements and certain data characteristics for life cycle assessments [23, 24]. However, this standard does not regard KPIs. Also, in most assessment methods the evaluation of data quality is limited to few aspects such as accuracy, precision and consistency [25].

The general standard ISO/IEC 25012 for data quality models comprises fifteen quality characteristics referring to the data domain, relationship of data values and metadata. [23] As concluded in ELSNER ET AL. the desirable use of primary data and the dynamization of sustainability assessments require additional data quality dimensions. This includes "time resolution," or a perspective change in the dimensions e.g. "consistency" [25]. EDELEN & INGWERSEN discuss data quality along all phases of life cycle assessments and introduce a data quality score and its implementation for data already in use. Nevertheless, it is stated that a system towards automated and interoperable data is needed. [19]

Considering the available papers, it is striking that – although data quality and common data usage is regarded as an important challenge of KPIs and sustainability assessments – only very few papers explicitly deal with data models or its implications for the definition of KPI sets.

2.4. KPI sets for sustainability assessments and evaluation of R-strategies in battery production

Since battery production poses a variety of processes and materials, no generalized KPI sets for sustainability assessment in battery production, that include the evaluation of R-strategies, are available yet. Some approaches and distinct KPI sets address the evaluation of CE feasibility e.g. the "Circularity Scoring System" and the "DigiPrime framework". [26, 27]

CRUZ UGALDE ET. AL. have proposed a "Circularity Scoring System" evaluating battery design and the remanufacturing by nine weighted criteria to evaluate the potential for repair and reuse, remanufacturing, or recycling. Yet, this system focuses on the evaluation of battery design, which does not cover all aspects of (re-)manufacturing. [26]

The "DigiPrime KPI framework" questionnaire depicts the need for data exchange across the value chain and the formalisation of KPIs. The defined KPI set comprises of twenty KPIs focusing on general requirements in the supply chain and not on (re-)manufacturing. Also data quality is not regarded despite the aim for common data usage across the supply chain, and the representation of the volatility of battery production is limited. [27]

2.5. Interim Conclusion & research gap

In the presented literature review of Section 2, it becomes clear that a common data basis, connecting the first life manufacturing and second life scenarios, must be created to establish the concept of CE in the batteries' life. Based on trustworthy sustainability assessments EoL decisions shall be enabled. While for manufacturing systems a variety of sustainability assessments are established, there is a lack of KPI sets considering the specifics of battery production and CE strategies. Necessary data requirements to ensure the trustworthy data base are rarely considered.

So far, few papers contribute to the research topic: GARRIDO-HIDALGO ET AL. developed a CE framework for electrical waste deriving requirements in CE approaches. Yet, the authors focus on the integration of digital technologies into sustainability approaches. [28] SOPHA ET AL. present a framework of challenges and assign enablers for CE in battery production. Focusing on a generalized framework for businesses within the supply chain, the authors remain on a high level perspective neglecting aspects of data access and quality [6]. KORNAS ET AL. define a KPI set for identifying cause-effect-relationships in quality deviations. The KPI set differentiates several levels but does not include environmental aspects [13]. Likewise, JENSEN ET AL. identify critical data for life cycle decisions. However, the scope excludes sustainability monitoring. [29]

Therefore, there is a demand for a consistent data basis for transparent KPI-based sustainability assessment covering the life cycle from production to second life and enabling funded decisions. In this paper the following research question shall be investigated: *What data quality requirements for KPIs and which KPI categories must be considered in KPI sets for sustainability assessment of first life battery production and second life remanufacturing enabling decisions on consecutive second life scenarios?*

The remaining paper is organized as follows: First, the methodology is presented (see section 3). In the main section 4, a KPI structure including data quality is presented to enable communication throughout the battery's life cycle (subsection 4.1). Additionally needed KPI categories for a holistic KPI set including remanufacturing and EoL decision making are presented in subsection 4.2. The section 5 provides a discussion of results and an outlook.

3. Research Methodology

The objective of this paper is to derive needed data quality aspects in the structural definition of KPIs enabling sustainability assessment in battery production throughout the life cycle as well as KPI categories addressing the use case perspective of volatile production and R-scenarios.

To adapt the structural definition of KPIs to fit the stated data needs, the standard structure of ISO 22400 [16] is systematically extended by the specific requirements of data quality and the FAIR data principles [30] that arise in the context of environmental sustainability assessments [25] and battery production life cycles including 2nd life scenarios. Two data quality implication matrices were derived: Matrix A maps the twelve data quality dimensions needed for dynamic sustainability assessments [25] and the four fair data principles [30] against the existing set of twenty KPI requirements [16]. Each pair was assessed regarding its implications for the paper's scope. As the KPI structure shall allow the use of common data throughout the batteries' life cycle, particular attention was paid to implications for the contextualization of data, accessibility, compliance, and traceability. Matrix B was set-up accordingly mapping each step of the battery life cycle including EoL, decision making, and possible R-strategies against the KPI requirements. [16] The two matrices can be made available by the authors.

The derived implications were assessed and categorized, defining additionally needed structural elements for the KPIs and adaptions of existing ones. The added and adapted structural elements were assigned to the content and context information sections in the KPI structure as well as to the new section "process", which was chosen based on [31].

To derive requirements for the KPI set the use case implications on the definition of KPI sets are analysed further. Based on expert discussions in workshops in the research project "QUGAPP," the two dimensions "CE feasibility" and "volatile production processes rich in variants" emerged to be regarded. The derived dimensions were validated by a search on review articles. Considering those boundary conditions, a structured literature review on enablers and barriers of circular economy in battery production was executed. This resulted in 116 articles using the search terms "electric vehicle," "battery" and "circular economy" in combination with one of the terms "barriers," "enabler," or "measures". After abstract (37) and full paper reading, 18 articles remained for the scope of this paper.

From these articles eleven enablers for CE in battery manufacturing were derived. For each enabler, implications for data quality were derived and mapped against the extended structural elements of KPIs to validate those. Additionally for each enabler the need for specific KPIs to address the regarded aspect in the context of EoL decision making and remanufacturing were assessed and categorized. In combination with existing KPI sets [3, 18] the categories form a framework to define a holistic KPI set for the environmental evaluation of battery (re-)manufacturing.

4. Results for the data structure and categories of KPIs for assessing battery (re-)manufacturing

The structure of KPIs and categories to be regarded in KPI sets for data-based sustainability assessments of battery (re-)manufacturing including the evaluation of possible 2nd use and 2nd life scenarios are presented in this section.

4.1. Integration of data quality in the structure of KPIs

To enable trustworthy KPIs for sustainability assessments, data quality dimensions applicable throughout the entire battery life cycle must be included in each KPI. ISO 22400 [16] defines a generalized structure for KPIs (adapted in Table 1). This KPI structure requests the definition of content related aspects, such as "name", and context information, e.g. "timing," or "audience". [16]

An analysis showed that the context information only partially covers the needed data quality aspects, as proposed by ELSNER ET AL. [25]. "Timing" covers the information of resolution for time specific assessments. "Audience" includes aspects of accessibility and meta data usage but is not adequately enough. The element "production methodology" must be redesigned towards "completeness" and "attributability." The context information "scope" needs to be adapted and gains in importance ensuring comparable results for decision makers. Overall, it can be stated that the dimensions completeness, uncertainty, attributability, responsibility, and accessibility are not regarded sufficiently.

To consider necessary data quality aspects for sustainability assessment of batteries, two data quality implication matrices were derived as described in section 3: In matrix A, the KPI requirements by the ISO were mapped against the data quality dimensions and the FAIR data principles [30]. In matrix B, the requirements were mapped against the product life cycle phases described in Fig. 1. The comparison resulted in 86 implications that can be categorized to ten additional KPI structural elements shown in Table 1.

Table 1. Extended table structure for a KPI based on ISO 22400 [16].

	KPI category	KPI function within sustainability assessments	Change in understanding
●	**Content:**	What?	
	Name	Identification	Unchanged
	ID	Identification & traceability	Unchanged
	Description	Comprehension	Unchanged
	Formula	Comparable in value chain	Unchanged
	Unit of measure	Comparability & allocation	Unchanged
	Range	Plausibility	Unchanged
◆	Data format	Connectivity	Interoperability
◆	Action trigger	Threshold decision trigger	Operational KPI
◆	Completeness	Evaluation of comparable assessment	Quantifiable statement needed
◆	Uncertainty	Evaluation of results' trust-worthiness for decisions	Quantifiable statement needed
●	**Context:**	Why?	
◆	Goal & trend	Description of KPI goal & direction of improvement	Added KPI contribution
◆	Use in decision	Need for specific KPI in which context	Added usage of KPI specification
◆	Hierarchy code	Classification of KPI within the overall KPI structure	Added categorization
◆	**Process:**	When–How–Who?	
●	Timing	Traceability over time toward KPI calculation	Timestamps per event
●	Production methodology	Product/process/system perspective	Assessment perspective
	Effect model diagram	Connection summary	Unchanged
●	Scope	System boundaries and inclusion criteria	Assessment scope
◆	Attributability	Definition of allocation unit	KPI allocation
◆	Responsibility	Responsibility for improvement	Decision maker
	Audience	Customer description	Unchanged
◆	Accessibility	Degree measure for access-ibility across supply chain	Assessment in addition to value
	Notes	Addition information	Unchanged

Key: ◆ Added structural element ● changed meaning or assignment

The derived elements are organized based on the "content, context, and process framework" [31]. The content elements remain unchanged: Elements to consider data format, completeness and uncertainty are proposed. The context dimension is being reorganized toward the KPI-usage: For example, KPIs are part of a whole KPI-system, so that each KPIs role should be specified by a standardized hierarchy code to enable allocation of KPIs on different system levels. The structure elements in the "process" section, assigned to the context dimensions in ISO 22400, are reorganized and supplemented by "responsibility" and "accessibility". Especially, "attributability" must be included so that the recombination of battery components for 2nd lives can be reflected in the KPIs. When applied, this extended KPI structure allows for common data usage and comparable assessments across all life cycle phases.

4.2. Categories to be regarded in KPI sets for sustainability assessments of battery (re-)manufacturing

Setting up a KPI set for sustainability assessments of battery (re-)manufacturing across all life cycle phases requires the consideration of general aspects of sustainability assessment and the aspects based on changes in 2nd life and 2nd use manufacturing. Holistic KPI sets for sustainability assessments in manufacturing have already been developed. [3, 18] Though to evaluate the aspects of changes in remanufacturing including the feasibility of R-strategies, their effectiveness, and the influence on sustainability performance, additional KPIs need to be defined. To derive additional needs, enablers for CE in battery manufacturing were analysed. [4, 6, 12] Each enabler was mapped against the life cycle phases and implications for the scope of this paper were derived for each pair. The full matrix with the evaluation of enablers and the implications for each life cycle phase can be made available by the authors.

The implications for KPIs derived by enablers of CE showed that the aspects on information sharing and data (infra)structure are thoroughly covered in the structural elements of the KPIs depicted in section 4.2 (see Table 2). This serves as validation of the structural elements derived.

All remaining implications were clustered to build categories for additional indicators to be included in holistic KPI sets for environmental sustainability assessments in battery (re-)manufacturing including the evaluation of the R-strategies. This resulted in the derivation of three additional overarching KPI categories, namely "modularity," "R-efficiency," and "status" as presented in Table 2.

Particularities of modular, flexible production systems needed for battery remanufacturing pose the need for a modular assessment of the battery packs and components, and an assessment on disassembly feasibility enabling easy decision making on EoL batteries. This cannot be addressed by existing general KPI sets for sustainability assessments. Hence the modularity of each battery pack shall be regarded. This allows for easy decision on disassembly depths as well as the evaluation of environmental footprint of individual modules and components enabling assessment of remanufactured batteries.

The environmental and economic feasibility and efficiency for different R-scenarios needs to be quantifiable resulting in an R-efficiency indicator for each module, battery pack and production line. This can include material recycling efficiency but also disassembly feasibility and the evaluation of additional environmental footprint by recycling or remanufacturing. This allows for a holistic evaluation of all life cycle phases and funded decision making.
Lastly, to enable decision making and tracking throughout batteries' life cycle, a status indicator of the battery (pack and module) needs to be defined, including uniform information such as "State of Health" and maximum capacity.

Table 2: Implications for the definition of KPI sets derived from CE barriers and enablers for EV battery manufacturing. Implications for data (infra)structure aspects (a), KPI categories for KPI sets regarding technology and infrastructure (b) and future regulations (c).

Enablers for CE	Implication for KPI set
(a) Data (infra)structure	**Coverage in KPI structural element**
Information digitalization [6] & traceability [3, 32]	Data format, accessibility, attributability
Standards on metadata formats, data quality and information interfaces [12, 32]	Addressed in various elements
EVB standards including compounds [6]	Range
Standardization of EoL process [6]	Scope
Policy & legislation on information sharing [6, 32]	Accessibility
Transparent product certifications [6]	Range, accessibility
(b) Technology and infrastructure	**Derived KPI category**
Battery modularization [6]	Modularity, R-efficiency
Proper status checking, diagnosing, and tracking [6]	Status (SoH, max. capacity, etc.)
Flexibilization of production lines [12]	Modularity, R-efficiency
(c) Policy and regulations:	**Coverage**
Legal environmental responsibilities [6]	In existing KPI sets

The derivation of the three additional indicator categories "modularity," "R-efficiency," and "status" set up in accordance with the newly extended structure for KPIs enables the adaption of holistic KPI sets for sustainability assessments to battery (re-)manufacturing and the extension to 2nd life scenarios.

5. Discussion of results and outlook on future research

In this paper, the different standards and frameworks for requirements for KPI sets were analysed and compared to the challenges of manufacturing companies regarding the requirements for Industry 4.0, sustainability assessment and its needed data quality dimensions. The generalized structure of a KPI defined by the ISO standard was extended to one consolidated set of 21 structure elements for the definition of KPIs to be used in the context of sustainability assessments for battery manufacturing and remanufacturing. By including the dimensions of data quality and FAIR data principles a common data structure per KPI set can be ensured. The interoperability of various KPIs and from different sources is essential. Hence, including the definition of an interoperable (meta)data format per KPI is strongly suggested when defining a KPI-set.

Additionally, KPI categories addressing the particularities of KPI sets in the context of CE and variant rich processes, such as the battery (re-)manufacturing, were analysed. Three additional KPI categories “modularity,” “R-efficiency,” and “status” were identified. When defining a KPI set not only the definition of KPIs for each allocation level but also interdependencies of KPIs, both within the allocation level and across the supply chain, need to be regarded. The newly derived KPI categories also display interdependencies, e.g. a modularity index can influence disassembly depth, which plays a major role in the feasibility of R-strategies. Hence it affects both modularity and R-efficiency. Therefore, in future research, a thorough analysis of interdependencies in each KPI set, e. g. in the model-effect diagram is needed for holistic evaluations and to enable strategic decisions for 2nd life scenarios. Additionally, the three depicted categories need to be extended to form KPIs on the different allocation levels enabling evaluation within each life cycle phase.

The number of structural elements and the need for additional KPI categories displays the complex framework for KPI-based sustainability assessment and decision making in the volatile and diverse environment of EV batteries. By defining the structure for each KPI and the KPI categories to be regarded, this paper provides the basis for the definition of a KPI set that can be used for transparent and comparable assessment in the battery (re-)manufacturing with common data usage across all life cycle phases. These assessments can serve as basis for decision making for 2nd life and 2nd use scenarios with the lowest environmental impacts.

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