Digital vehicle passports for circular value chains: preliminary concept and use cases

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ABSTRACT

This paper presents a preliminary concept for a digital vehicle passport (DVP) of an electric vehicle (EV), abstracting major vehicle components by delineating information requirements needed to support respective circular and sustainable product management. Furthermore, three practical DVP use cases are presented, representing major vehicle life cycle phases. The concept development was driven by a systematic stakeholder mapping, enabling to identify key stakeholders of the EV (component) value chain(s). A systematic literature review enabled the identification of sustainable and circular EV (component) management practices and information requirements for respective support. Those information requirements were synthesized in an abductive approach. This resulted in a DVP concept comprising three main information categories. Furthermore, the developed concept emphasizes a DVP orchestration via subsuming digital product passports (DPPs) of EV components (e.g., digital battery passport, digital e-motor passport, digital tyre passport, etc.), exploiting data synergies. This paper contributes to current DPP literature in a sustainable product management context, as it presents the first conceptualization of a complex multi-component product. Thus, it distinguishes itself from current DPP research, that mainly focuses on energy storage systems or the built environment. The paper further holds practical relevance for regulators and practitioners as it highlights sustainable product management use cases and respective information requirements.

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1. INTRODUCTION

Powertrain electrification is considered as one of the major technologies contributing to the decarbonization of the transport sector (Gerlando et al., 2024). Consequently, it is of interest to manage electric vehicles (EVs) with focus on maximising their sustainability and circularity performances, counteracting potentially undesired sustainability impacts (Rusch et al., 2023). EVs are complex multi-component products, complicating respective sustainable product management (SPM) (Gerlando et al., 2024). Each component stems from a different value chain comprising various value chain actors, who are facing different and at times competing SPM strategies and pathways (Hirz & Brunner, 2015). To support the identification of suitable and viable SPM pathways, value chain actors require, among others, high-quality data (Rusch et al., 2023). However, persisting data and information gaps along value chains prove great challenges for SPM (ibid). Digitalization, digital technologies and tools could prove valuable to collect, store, process and analyse product life cycle data, bridging data gaps along the value chain and enabling circular information flows (Rusch et al., 2023). Emerging tools like the digital product passport (DPP) could prove valuable in functioning as data carrier of product life cycle data, bridging data gaps along value chains, and facilitating collaboration among value chain actors (Berger et al., 2022). Sustainability research (Berger et al., 2022; Çetin et al., 2023), initiatives (The Battery Pass, 2024) and regulators (European Commission, 2023) have brought forward different proposals of DPPs for SPM practices in value chains. Major focus is placed on batteries (Berger et al., 2022; European Parliament, 2023; The Battery Pass, 2024) or the built environment (Çetin et al., 2023). However, complex multi-component products such as EVs have received so far limited attention. While from a regulatory side, the notion of a circular vehicle passport (CVP) has been introduced (European Commission, 2023), a DPP comprising a holistic sustainability perspective (i.e., environmental sustainability, social sustainability) for an entire EV has received so far no attention on a regulatory context nor in sustainability research.

This paper sets out to present a preliminary concept of a digital vehicle passport (DVP) in the context of SPM, answering the following research question:

RQ: *How needs a digital vehicle passport to be orchestrated in terms of key information to support the sustainable product management of an electric vehicle?*

Regarding the DVP scope the following major EV components were selected to be represented, based on an initial desk research (Gerlando et al., 2024;

Wen et al., 2021) and consulting policy papers (European Commission, 2023): the e-motor, power converter/inverter, brake system, battery pack, and tires.

The subsequent sections present the theoretical background (section 2), the method description (section 3), followed by the results' presentation (section 4). The paper closes with discussion and conclusion (section 5).

2. THEORETICAL BACKGROUND

2.1 THE ELECTRIC VEHICLE VALUE CHAIN AND SUSTAIN-ABILITY MANAGEMENT

EVs are products that consist of a range of multi-component parts, enabling certain performances (e.g., driving range, charging duration, acceleration times), while fulfilling technical (e.g., weight, size) and safety requirements (Hirz & Brunner, 2015). Major EV components are the e-motor, the EV battery, converters and inverters, brake systems, as well as tires (Wen et al., 2021). Each of those components consist of different parts and materials that require different processes for being produced. For instance, an e-motor contains permanent magnets that require critical rare earth materials (Wen et al., 2021). An EV battery entails different active materials (e.g., lithium, cobalt, iron, manganese, graphite) to produce respective battery cells (ibid). The brake system, on the other hand, requires ceramics, rubber and steel for component production (NRS Brakes, 2023). Consequently, a holistic sustainable EV management constitutes the sustainability-oriented product management of all vehicle components, contributing to the EV's overall sustainability and circularity performance. Such an effort may pose challenging, due to the complexity of SPM decisions that concern not just one component, but multiple components that in turn constitute of different parts (Hirz & Brunner, 2015). Here, various decision-makers along the component value chains may face competing sustainability decision situations, while keeping performance and safety requirements, as well as economic viability into consideration (ibid).

2.2 DIGITAL TECHNOLOGIES AND TOOLS FOR SUSTAINABLE PRODUCT MANAGEMENT: THE CASE OF THE DIGITAL PRODUCT PASSPORT

When maximising a product's (environmental and social) sustainability and circularity performance, a holistic system's perspective is required (Rusch et al., 2023). There are different established concepts and approaches that can support such a fundamental product system transformation, including circular economy, sustainable supply chain management, life cycle assessment, or design for X (e.g., sustainability, circularity) approaches (ibid). Those approaches can be subsumed by the umbrella term SPM, taking into consideration a holistic life cycle approach and the perspective of various value chain actors over (potentially) multiple life cycles (Berger et al., 2022). One of the major challenges of SPM is the lack of high-quality product life cycle data for respective decision support (Rusch et al., 2023). In this context, the sustainability research stream exploring the potential of digitalization and digital technologies to enable SPM actions is continuously growing (ibid).

Recently, the digital tool entitled "digital product passport" has gained increased attention in sustainability research. DPPs are perceived as digital enablers of a sustainable circular economy, as they are envisioned as product life cycle data carrier (Berger et al., 2022). Some studies have already provided DPP conceptualization attempts to enable SPM in the construction sector (Çetin et al., 2023) or the automotive sector (Berger et al., 2022). For instance, Berger et al. (2022) provided a concept of a DPP for EV batteries, comprising four main information categories (cf. Table 1).

DPPs for multi-component products, such as EVs, are currently proposed from a regulatory perspective. Here, the CVP (European Commission, 2023) and environmental vehicle passport (EVP) need to be mentioned (European Commission Council, 2022). While those DPP-variants focus on the entire vehicle, they do not comprise a holistic sustainability perspective, focusing on conveying selective sustainability aspects (i.e., circularity – CVP, legal compliance emission level – EVP). A proposal brought forward by the World Economic Forum to merge the CVP and EVP led to coining the term "digital vehicle passport" (World Economic Forum, 2024). However, it is to be questioned whether a DVP based on DPP-variants that do not take into account a holistic sustainability perspective, can effectively support SPM.

Table 1: DPP information categories in accordance with Berger et al. (2022).

Information category	Description
Battery	Contains information to enable clear product identification, thus contextualization (e.g., technical specifications, performance specifications material compositions, etc.)
Sustainability and circularity	Contains information about the product in terms of sustainability and circularity properties (e.g., indicators relating to sustainability and circularity performances, information regarding disassembly to facilitate R-strategies, etc.)
Diagnostics, performance and maintenance	Contains information about the system status (e.g., state-of-health), maintenance triggers and carried out maintenance measures
Value chain actors	Contains information about value chain actors involved (e.g., value chain actor name, location, identification number, function)

3. METHODS

The DVP concept was developed based on the conceptualization approach proposed by Berger et al. (2022). First, a systematic stakeholder mapping in accordance with the supply chain-oriented process to identify stakeholders (SCOPIS) was conducted (Fritz et al., 2018), identifying value chain actors involved in the following EV component value chains: e-motor, power converter/inverter, brake system tires. The SCOPIS (incl. identification data needs and requirements for SPM) for the EVB has been conducted in a previous study (Berger et al. 2022). SCOPIS was supported by a systematic literature review (Moher et al., 2009). This enabled the identification of value chain actors' potential SPM use cases, and respective data needs and requirements. SCOPIS and the systematic literature review were conducted between December 2024 and March 2025. Literature written in German and English language were eligible for the literature sample. Both, scientific and grey literature were included. Scientific literature (i.e., journal papers, conference papers) was identified by using the database Scopus. The identification of suitable grey literature (e.g., websites, product specification sheets, white papers, company reports) and respective sources was supported by a knowledge resource nomination worksheet approach (Okoli & Pawlowski, 2004) and the search engine google.

The deployed keywords led to initially 1053 hits. To be considered relevant, the records had to have a clear focus on the automotive sector. Records that focused on other sectors (e.g., energy sectors – wind turbines, aircrafts, electronics – dough makers) were excluded. The records required clear reference to the EV components of interest, enabling to derive information about the product and material structure. Records were also included if they described respective component value chains (upstream, downstream, full value chain) or life cycles (beginning-of-life, middle-of-life, end-of-life). Records that provided superficial information (e.g., "component xy is important”) were excluded. Records were considered that discussed the selected components considering sustainability management (incl. circular economy) and respective strategies (e.g., life cycle engineering and management, life cycle assessment). Based on this criteria, 185 records remained after the title screening. Of those records the abstracts were screened. Based on the inclusion and exclusion criteria 31 records remained. Those records were then screened in their entirety, leading to a final sample of N = 20 scientific records. The grey literature search led to identifying N = 32 records, deemed relevant to support SCOPIS, as well as to identify information requirements for supporting SPM along the EV value chain. Thus, the final literature sample comprised N = 52 records. SCOPIS was supported by applying a life cycle perspective, deductively clustering the identified stakeholders, SPM decision pathways, and identified information requirements based on the following life cycle phases: beginning-of-life (BoL), middle-of-life (MoL) and end-of-life (EoL). Based on the SCOPIS findings, the conceptualization of the DVP was carried out following an abductive approach. As the deductive theoretical framework served the information categories proposed by Berger et al. (2022) (cf. Table 1). The identified information requirements were clustered based on those pre-defined information categories. The inductive character is given, as during data point clustering new information categories were developed, which are absent in Berger et al. (2022).

4. RESULTS

3.1 PRELIMINARY DIGITAL VEHICLE PASSPORT CONCEPT

The DVP concept comprises in total three main information categories: “vehicle”, “sustainability and circularity - overall system”, and “diagnostics, maintenance, and performance – overall system”. As the deployment of DPPs will become mandatory for certain products (e.g., battery, tires, steel-based products, aluminum-based products), DVP orchestration should be supported by EV component level DPPs (e.g., battery passport, tire passport, etc.), containing component-based information in the context of SPM. The component-specific DPPs can be considered as independent systems, that function as data sources for the DVP system that enable data synergies. Consequently, the component-specific DPPs comprise of main information categories themselves namely: “product”, “sustainability and circularity”, “diagnostics, maintenance, and performance”, and “value chain actor”. The component-specific DPPs serve to access detailed component-specific information, in particular in terms of sustainability and circularity performances, as well as component health and diagnostics. If component-specific DPPs are unavailable, the required information needs to be included in the DVP system. A visual representation of the DVP concept is depicted in Figure 1. A more detailed concept description is provided in following subsections.

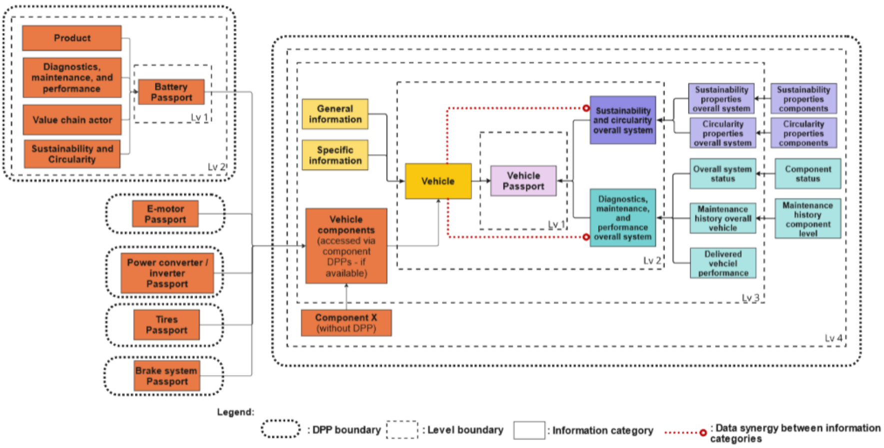

Figure 1: Digital vehicle passport concept. Depiction based on Berger et al. (2022).

3.2 VEHICLE

This main information category comprises two subcategories, namely "general information" and "specific information". The first subcategory contains data points about general EV features, such as *vehicle class (*e.g., passenger car, heavy duty*), vehicle type (*e.g., battery EV, plug-in-hybrid EV*), vehicle manufacturer, location of assembly*. The second subcategory comprises data points related to vehicle performances (e.g., *driving range, EV lifespan, dis-/charging times, etc.*), technical specifications (e.g., *dimensions, weight (curb weight, dry weight)*). Those two subcategories enable a clear product identification, which is a pre-requisite in SPM.

This category also contains the subcategory "vehicle components", comprising information about major EV components including: the EV battery, e-motor, power converter/inverter, tires and brake system. For each EV component there is a respective information category (e.g., "Battery", "E-Motor", etc.) containing the following component specific information categories: "product", "sustainability and circularity", "value chain actor", as well as "diagnostics, maintenance and performance" (cf. Figure 1). Thus, information ranging from component identification, technical specifications, over sustainability and circularity performances on component level, component health, as well as value chain actors involved can be accessed.

3.3 SUSTAINABILITY AND CIRCULARITY – OVERALL SYSTEM

This main information category comprises two subcategories: "sustainability properties – overall system" and "circularity properties – overall system".

The subcategory dedicated to sustainability distinguishes two sustainability performances; "environmental sustainability performance – overall system" and "social sustainability performance – overall system". Those information categories enable to derive information in terms of respective sustainability performance, i.e., *indicators and results* (e.g., carbon footprint, water use, land use) of the overall EV. This is complemented by information about applied *standards and impact assessment methods* (e.g., ISO, UNEP). As the EV comprises different components, contributing to the overall sustainability performance, this category enables accessing information about the component-specific sustainability performances. This establishes a link between the information category "sustainability and circularity – overall system" and the component-specific DPPs' information category "sustainability and circularity". Thus, the component-specific DPP serves in particular as data source for the DVP subcategory "sustainability properties – component" (cf. Figure 1). Here, further information can be derived regarding the component-specific sustainability indicator results, as well as the life cycle hotspots. Thus, the DVP enables the identification of (i) critical components, and (ii) their respective critical life cycle processes. This serves to identify areas for potentially enhancing the EV sustainability performance.

The subcategory dedicated to circularity comprises two categories: "circularity performance – overall system" and "circularity support – overall system" (cf. Figure 1). The category "circularity performance – overall system" provides information about the overall EV circularity performance and allowing the identification of components' contribution to the overall EV circularity via its subcategory "circularity performance-component". The category "circularity support – overall system" contains information about the EV design, down to the component level. Thus, component-specific data points with respect to *disassembly options and instructions*, as well as *repair options and instructions* can be found in this category. Here, the component-specific DPPs also serve as data source for the DVP subcategory dedicated to circularity properties.

3.4 DIAGNOSTICS, MAINTENANCE, AND PERFORMANCE – OVERALL SYSTEM

This main information category comprises the subcategories "overall system status", "delivered vehicle performance", as well as "maintenance history – overall system". The subcategory "overall system status" provides vehicle diagnostic information, further enabling to derive more detailed component-level diagnostics information due to the linkage of component-specific DPPs (cf. Figure 1). A similar logic applies to the other two subcategories, as the component level of an EV plays a crucial role regarding overall EV system status. The subcategory "maintenance history – overall system" thus enables to derive component-specific data points such as *maintenance triggers*, *carried out maintenance action,* and *responsible party for maintenance action*. The subcategory "delivered vehicle performance" contains data points such as *actual range covered*, or *actual dis-/charging time*, enabling a comparison between the stated EV (component) performance according to the manufacturer and the field performance.

3.5 DIGITAL VEHICLE PASSPORT: USERS, SPM USE CASES AND CONCEPT UTILITY

In the BoL phase, the manufacturers of the EV components (e.g., e-motor, brake system, inverter/converter, tires), as well as the EV manufacturer themselves were identified as key decision makers. As they can opt to include sustainability and circularity requirements in the EV (component) design of next-generation EVs. The manufacturers require information about the environmental and social sustainability performance over the entire vehicle (component) life cycle, enabling the identification of life cycle hot spots. This aids to identify optimization potentials in the own production processes, as well as the overall product (component) design (e.g., material selection, design for X). Furthermore, it enables identifying (potential) life cycle processes, and consequently suppliers, that require supplier development measures (e.g., trainings for sustainability education) to contribute to the product system's overall sustainability and circularity. Here, the manufacturers can derive utility from DVPs of current in-use EVs. Here, the information category "vehicle" for EV identification, and thus contextualization is the first category of importance. Furthermore, the information category "sustainability and circularity – overall system" enabling to derive the sustainability and circularity performance on EV and component level.

In the MoL phase, the EV driver was identified as prospective DVP user. The EV driver may require information about the sustainability performance (e.g., CO_2 footprint of the EV production, estimated energy consumption during the use phase, information about child labour and forced labour involved during production, etc.) and circularity performance (e.g., share of recycled material, share of reused material) to support an EV buying decision. Also, general information about the EV (e.g., technical aspects, performance aspects) may further support the buying decision process. In case of buying a second hand EV, information about the product system's health status is of interest (e.g., maintenance work done, triggers for maintenance work, rest of (estimated) lifetime of the EV or key components, such as the battery). Here, the main information categories "vehicle", "sustainability and circularity - overall system", and "diagnostics, maintenance, and performance – overall system" can provide respective information.

For the EoL phase, in particular recyclers as well as refurbishing and repurposing parties were identified as actors of importance. Refurbishing and repurposing parties (e.g., the EV manufacturer, a third party) can contribute to either restore the EV component for reuse (e.g., tires – retreading) or to repurpose the component for a second life application (e.g., EV battery – as stationary energy storage system). Here, the main information categories "vehicle", "diagnostics, maintenance, and performance-overall system", as well as "diagnostics, maintenance, and performance-component" are useful, enabling to derive health status-related information. Furthermore, the information category "sustainability and circularity – overall system" and its subcategory "circularity support overall vehicle" are beneficial to provide information (e.g., information about dismantling instructions) required for efficient repurpose/refurbishment operations of EV components. The recycler resumes a vital role as they will treat the EV (component), enabling to recover secondary material for primary material substitution in the EV value chain. Recyclers require information about the product composition (e.g., bill of material), as well as information about how to (safely) dismantle the EV component, enabling the design of an efficient recycling process. Here, the information categories "vehicle" and "sustainability and circularity – overall system" and its subcategory "circularity support overall vehicle" are useful.

5. DISCUSSION AND CONCLUSION

The presented DVP concept distinguishes itself from current conceptualization attempts (e.g., Berger et al., 2022) as it focuses on a multi-component product. Compared to the concept proposed by Berger et al. (2022), this DVP concept considers information representing the overall product level (i.e., the entire vehicle), as well as a component-based level. Furthermore, the DVP concept presented differentiates itself from current regulatory proposals (e.g., European Commission, 2023), and NGO recommendations (World Economic Forum, 2024) as it incorporates a holistic sustainability perspective. That said, the proposed DVP concept does not necessarily exclude regulatory use cases (e.g., European Commission, 2023), but goes beyond regulatory required information content, enhancing the SPM support potential of DVP. Furthermore, when conceptualizing a DPP of a multi-component product that consists of different (multi-)components itself, the DPP orchestration needs to be considered. Here, such an orchestration could be supported by integrating (existing) DPPs of those components, that constitute the overall product. Thus, a DVP would be orchestrated by exploiting DPPs of major EV parts, i.e., a digital battery passport, digital e-motor passport, digital tire passport etc. Those component-based DPPs contain component-specific information, providing a comprehensive representation of the entire EV. Thus, the component DPPs are to be seen as the underlying data source of a DVP, enabling the exploitation of data synergies. If no component-specific DPP is available, the DVP system would require the integration of component-specific information (cf., Figure 2).

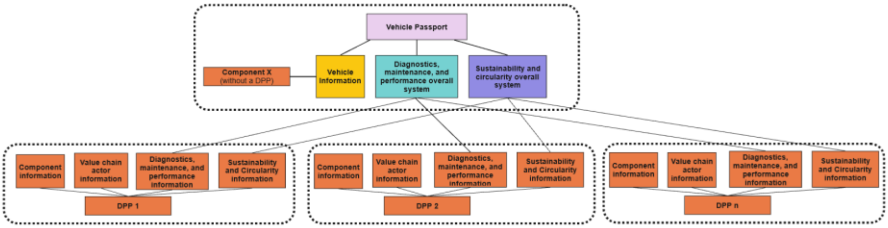

Figure 2: Orchestration of a DPP of a multi-component product via respective component-specific DPPs (own depiction).

This paper holds practical relevancy as it may provide guidance for policy makers and practitioners, when pursuing DPP implementation for SPM due to emphasizing the need of taking a holistic sustainability perspective into consideration. Considering a research perspective, this paper provides the foundation to further develop and refine multi-component DPPs for SPM support.

The major limitations lies in the conceptual nature of this work. Here, empirical validation is required (e.g., by directly involved EV value chain actors) to discuss the concept utility for SPM. Furthermore, further research regarding DVP orchestration and implementation is needed, considering the incorporation of component-specific DPPs. This further includes the design of the DVP and DPP system architecture and respective data security and accessibility issues.

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REFERENCES

Berger, K., Schöggl, J.-P., & Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases.

Journal of Cleaner Production, 353(February), 131492. https://doi.org/10.1016/j.jclepro.2022.131492

Çetin, S., Raghu, D., Honic, M., Straub, A., & Gruis, V. (2023). Data requirements and availabilities for material passports : A digitally enabled framework for improving the circularity of existing buildings. Sustainable Production and Consumption, 40(July), 422–437. https://doi.org/10.1016/j.spc.2023.07.011

European Commission. (2023). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on circularity requirements for vehicle design and on management of end-of-life vehicles, amending Regulations (EU) 2018/858 and 2019/1020 and repealing Directives 2000/53/EC and 2005. https://www.europarl.europa.eu/news/en/press-room/20240308IPR19017/euro-7-parliament-adopts-measures-to-reduce-road-transport-emissions

European Commission Council. (2022). Regulation of the European parliament and of the council emissions and Battery durability (euro 7). Official Journal of the European Union, 0365(715).

European Parliament. (2023). Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC. Official Journal of the European Union, 66(L191), 1–117. http://data.europa.eu/eli/reg/2023/1542/oj

Fritz, M. M. C., Rauter, R., Baumgartner, R. J., & Dentchev, N. (2018). A supply chain perspective of stakeholder identification as a tool for responsible policy and decision-making. Environmental Science and Policy, 81, 63–76. https://doi.org/10.1016/j.envsci.2017.12.011

Gerlando, A. Di, Gobbi, M., Chiara Magnanini, M., Mastinu, G., Palazzetti, R., Aqeab Sattar, ·, Tolio, T., & Magnanini, M. C. (2024). Circularity potential of electric motors in e-mobility: methods, technologies, challenges. Journal of Remanufacturing 2024 14:2, 14(2), 315–357. https://doi.org/10.1007/S13243-024-00143-6

Hirz, M., & Brunner, H. (2015). ECO-Design in the Automotive Industry – Potentials and Challenges. Paper Presented at MOSTOP 2015, June.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med, 6(7), b2535. https://doi.org/10.1136/bmj.b2535

NRS Brakes. (2023). Are Brake Pads Still Necessary for Electric Vehicles? https://nrsbrakes.com/blogs/blog/rethinking-brake-pads-are-they-necessary-for-electric-vehicles

Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool : an example , design considerations and applications. Information & Management, 42(1), 15–29. https://doi.org/10.1016/j.im.2003.11.002

Rusch, M., Schöggl, J.-P., & Baumgartner, R. J. (2023). Application of digital technologies for sustainable product management in a circular economy: A review.

Business Strategy and the Environment, 32(3), 1159–1174. https://doi.org/10.1002/bse.3099

The Battery Pass. (2024). Battery Passport Technical Guidance The Battery Pass consortium.

Wen, W., Yang, S., Zhou, P., & Gao, S. Z. (2021). Impacts of COVID-19 on the electric vehicle industry: Evidence from China. https://doi.org/10.1016/j.rser.2021.111024

World Economic Forum. (2024). Enabling Automotive Circularity through Digital Vehicle Passports (Issue January).