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A Conceptual Framework for Sustainable Integration of Electric Vehicles and Energy Systems through Product Lifecycle Management (PLM)

Rodinaldo Ferreira dos Santos[a,*], Henrique Luís Sauer Oliveira[b], José Antonio Valle Antunes Junior[a], Miguel Afonso Sellitto[a], Debora Oliveira da Silva[a], Romeo Bandinelli[c], Virginia Fani[c]

[a]Universidade do Vale do Rio dos Sinos (UNISINOS), Av. Unisinos, 950 - Cristo Rei, São Leopoldo - RS, 93022-750, Brazil.
[b]Universidade Federal de Santa Maria (UFSM), Av. Roraima nº 1000 Cidade Universitária Bairro - Camobi, Santa Maria - RS, 97105-900, Brazil.
[c]Università di Firenze (UNIFI), P.za di San Marco, 4, Firenze FI, 50121, Italy.
rodisantos@edu.unisinos.br

With the advancement of electric mobility, the search for renewable energy sources becomes even more critical. A strategic management tool that can support the integration between mobility and energy concerns is Product Lifecycle Management (PLM). It may serve as a strategic link in integrating complex systems, such as electric mobility and sustainable energy systems. A search in databases identified a research gap in the use of PLM for integrated management between electric vehicles (EVs) and energy systems. Having identified this opportunity, this article presents a conceptual framework that will serve as a guide and support tool for managers, researchers, and other stakeholders in decision-making regarding the integration of EVs and sustainable energy sources throughout their life cycle. To assist in the identification of the problem, in the design of the solution, and in the evaluation and validation of the proposed framework, the Design Science Research (DSR) method was used, which helps in the solution of practical and relevant problems through the construction and evaluation of artifacts, in addition to contributing to the creation of scientific knowledge. The result is a framework that enables mapping the life cycle of EVs, identifying connection points with bioenergy sources, evaluating energy flows based on sustainability indicators, defining system integration strategies, and simulating the impact of efficiency scenarios. This approach will support decisions that balance the integration of EVs and sustainable energy systems.

1. Introduction

Global efforts aim to reduce greenhouse gas emissions. Sustainable mobility is one of these spheres, and integration with renewable energy systems is an opportunity for the transition to low-carbon economies (Anvari et al., 2025; Raman et al., 2025). Bioenergy and electric vehicles (EVs) are emerging technologies that can help reduce greenhouse gas emissions and promote energy diversification. Despite being two important channels in technological progress, fragmentation in the integration between them is observed, especially in emerging markets (Marinelli et al., 2021; Aldosari et al., 2024; Ullah et al., 2025). One approach that has proven crucial in integrating people, processes, and data throughout all stages of a product's life cycle is Product Lifecycle Management (PLM). It is a strategic management system that enables the product to be evaluated from design through to the end of its useful life (Saad and Youness, 2024). It is a system widely applied in manufacturing, technology, and digital transformation; however, despite its potential, its use in supporting sustainability transitions, especially in energy and mobility, remains underexplored (Seegrün et al., 2024). Several studies highlight that PLM plays a crucial role in improving tracking processes, enhancing communication efficiency, and boosting performance in the circular economy. Despite this, when it comes to existing structures, most treat industrial processes in isolation, without a systemic approach that connects vehicle lifecycle management and

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renewable energy (Cholewa and Minh, 2021). To seek sustainable integration between electric mobility and bioenergy systems, a framework proves to be an essential way, as long as it is used, to improve product life cycle visibility, energy efficiency and support decisions related to sustainable innovation. The conceptual framework serves as a guide for understanding, analyzing, and developing a phenomenon, method, or system. It organizes and connects the main concepts of a theme and their relationships (Delafield et al., 2021). Therefore, the objective of this research is to develop a PLM conceptual framework that enables the sustainable integration of electric mobility and bioenergy systems. The article is divided as follows: In section 2, Materials and Methods are presented; In section 3, the Results and Discussions; and in section 4, the Conclusions.

2. Materials and Methods

2.1 Design Science Research

The method of choice for this research was Design Science Research (DSR). It is a research approach that focuses on the creation and validation of artifacts, with two evident purposes in relation to research: problem-solving and scientific discovery (Gauss et al., 2025). Research using DSR has four main objectives: (i) (re)framing, which seeks to relate the problem, its causes, and consequences to new or existing references. It helps to change the way we think about the issue, making it possible to find new solutions, it provides a gateway to discovering and understanding a problem; (ii) create, which is related to the change of a system from its current state to a new one; (iii) validation, which is related to the submission of the model to empirical tests and comparison with a real system; and (iv) theorizing, which is related to testing and refining abstract ideas based on empirical evidence (Romme and Dimov, 2021). DSR is structured in six interactive and complementary stages that contribute to the development of knowledge: (1) identification and motivation of the problem; (2) definition of the objectives of the solution; (3) design and development; (4) demonstration; (5) evaluation; and (6) communication. These steps make up the central methodological axis of contemporary SRD (Gregor and Zwikael, 2024). DSR is known for the continuous development of knowledge, for allowing the exploration of the occurrence of a new or modified artifact, through incipient design theory to complete design theory, it focuses on adding knowledge on how people can and should develop and organize things to achieve a desired goal (Gregor and Zwikael, 2024; Maedche et al., 2021). Because it aims to create both theoretical and practical artifacts, the DSR method for constructing a framework is an appropriate approach, as it yields useful, scientifically grounded knowledge. Its application does not aim to test hypotheses, but to structure and formalize conceptual solutions (Gregor and Zwikael, 2024; Tuunanen et al., 2024). In this way, DSR provides an appropriate methodology for developing a systematic, integrative framework (Goecks et al., 2024), linking PLM, electric mobility, and renewable energy systems, aligning theory with future applicability.

2.2 Product Lifecycle Management

PLM is a strategic approach that enables analysis from product design to the end of its lifecycle, ensuring cohesion in traceability and interoperability between engineering, production, and data management systems (Fani et al., 2021; Sellitto et al., 2022). Amid environmental, regulatory, and social pressure, integrating PLM into sustainability is critical (Seegrün et al., 2024). It has become an essential component for companies operating in the renewable energy sector and electric mobility, facilitating exploration of battery maintenance throughout the life cycle and opportunities for the product's second life (Prause and Gerlitz, 2024; Silchenko, 2024).

2.3 Electric Mobility

Electric mobility is associated chiefly with electric vehicles. They are vehicles powered exclusively by batteries, plug-in hybrids, and fuel cells. They can be light, such as motorcycles and cars, or larger, generally used for deliveries and passenger transport. These categories demonstrate the breadth of electric mobility and the extent to which the proposed framework can be applied to the analysis of each of them, considering that the electric motor and battery pack are vital components in electric vehicles (Rani and Jayapragash, 2024). Given its importance, electric mobility requires attention to the life cycle of cars, batteries, charging infrastructure, and integration with energy systems. The use of electric vehicles necessitates data integration, traceability, and a robust information foundation, given that their adoption has implications across technological, environmental, organizational, and political dimensions (Zaino et al., 2024). Electric mobility is not just a vehicular issue, but also involves the energy life cycle, technological sustainability, and strategic decisions.

2.4 Sustainable Energy

The concept of sustainable energy is closely tied to systems based on renewable sources, including solar, wind, biomass, and hydrogen, among others. Hybrid integration of clean sources is considered a way to reduce

emissions and dependence on fossil fuels. Multigeneration solutions can increase energy efficiency and reduce losses, thereby improving storage and, consequently, stability and overall performance (Anvari et al., 2025). Associated with electric mobility, wind and solar energy can be integrated into electric vehicle charging stations, strengthening sustainable energy infrastructure, fueling clean mobility, and driving the vehicular energy transition (Ullah et al., 2025). Electric mobility and sustainable energy should be viewed as interdependent systems, rather than isolated ones.

2.5 Framework

The framework is an organizing structure that explains how variables, constructs, or processes relate to one another within a system, rather than a mathematical or empirical model. It is a conceptual artifact created to structure and represent knowledge about complex problems. They are designed to guide analyses, decisions, and future applications, offering practical utility and theoretical validity (Gauss et al., 2025; Gregor and Zwikael, 2024). Frameworks help identify knowledge gaps and guide sustainability policies and practices, enabling the systematization of fragmented knowledge and the transformation of dispersed structures into actionable frameworks (Seegrün et al., 2024b). They offer conceptual clarity and strategic direction, facilitating research development and the formulation of sustainable solutions in sectors such as electric mobility and energy. Thus, the proposed framework was built with the same purpose: to organize complex concepts related to PLM, electric mobility, and sustainable energy into an understandable, applicable structure.

3. Results and discussion

3.1 Framework development

The literature demonstrates that conceptual models are frequently employed in engineering and environmental studies to structure complex phenomena. While existing frameworks often treat PLM, electric mobility, and energy systems in isolation, the novelty of this research lies in proposing a systemic integration of these three dimensions. This model goes beyond traditional approaches by establishing a cohesive structure that connects vehicle lifecycle management directly with renewable energy sources, supporting future decision-making and helping researchers develop studies on the product life cycle by structuring indicators, data flows, and results. To promote this integrated vision, a conceptual framework is presented in Figure 1.

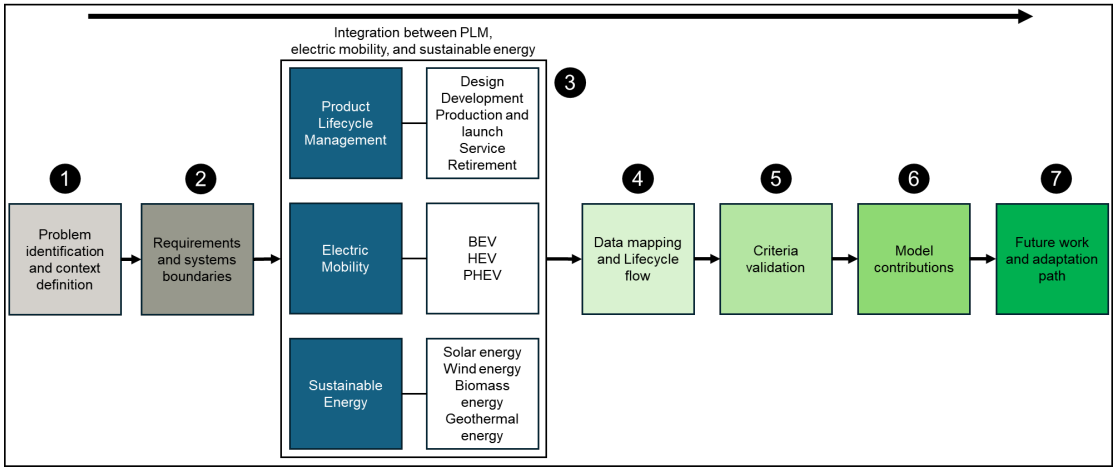


Figure 1: Proposed framework and its seven steps.

The framework was developed based on the principles of DSR. It consists of seven interconnected steps, ranging from identifying the problem to proposing future research paths. Each step plays a specific role in the artifact development process. It ensures that the practical application and methodological rigor are aligned with the theory. Next, the details of each phase are presented.

3.2 Step 1: Problem identification and context definition

The first stage of the framework involves contextualizing the research problem, serving as a basis for the subsequent stages. In this phase, the focus is on understanding the relevance of integrating PLM, electric mobility, and sustainable energy to identify the current context and the gaps in the literature and practice. For the construction of the artifact, the clarity of the problem becomes essential, as this phase seeks to characterize the objectives and central challenges.

3.3 Step 2: Requirements and systems boundaries

Step two of the proposal addresses the definition of the research requirements and limits. The importance of this phase lies in translating, based on the problem, the technical and strategic requirements necessary to conduct the study. Integration points, performance expectations, and stakeholder needs are all examples of data to use. The system to be modeled is also delimited in this phase. The researcher will explore the boundaries of the defined scope, research constraints, levels of analysis, and key components of research. Alignment with the method described is essential to meet the relationship criteria, process variables, and identify related dependencies. This phase is necessary for the framework to be applied effectively, enabling the mastery of its application, providing necessary responses to stakeholders, and incorporating robust elements for informed decision-making.

3.4 Step 3: Integration between PLM, electric mobility, and sustainable energy

Step three involves constructing the core artifact of the research: integrating PLM with electric mobility and sustainable energy. It consists of integrating the requirements defined in the previous step. This phase is considered the design stage, in which the elements are organized into a conceptual model, generating connections that enable integration among the dimensions studied. Its purpose is to transform requirements into a logical artifact that can be integrated into the product life cycle. The foundation is based on practical applicability aligned with scientific rigor, consolidating into an integrating model.

3.5 Step 4: Data mapping and lifecycle flow

The concentration of step four is linked to the mapping of data related to PLM, electric mobility, and sustainable energy. It represents the information flows and interactions between the defined modules. The life cycle map enables you to visualize the generation, sharing, and utilization of information throughout each phase of the product's lifecycle. From this, the integration of PLM, electric mobility, and sustainable energy systems is evident, providing a clear view of the critical points and the need for improvement. The importance of this stage lies in demonstrating the coherence between the conceptual components of the framework and its practical application, thereby enabling its evaluation in future stages.

3.6 Step 5: Criteria validation

The focus of step five is the evaluation and validation of the framework, ensuring that the artifact meets the criteria of rigor and relevance established in the DSR. The importance lies in analyzing conceptual coherence, internal consistency, and the potential for practical application, specifically in the integration of PLM, electric mobility, and sustainable energy systems. It aims to validate the relationship between the data collected and the identified needs. Theoretical and practical validation procedures are evaluated by experts in the field, and the methodological robustness of the framework is ensured. This enables the identification of opportunities for improvement and establishes its value as a tool to support research.

3.7 Step 6: Model contributions

Step six focuses on presenting the model's contributions to demonstrate its impact on academic and professional circles. It is expected that, at this stage, the conceptual framework can be translated into practical guidelines, enabling researchers and managers to understand how to apply the techniques and interpret the results. It demonstrates the practical value of the artifact, offering guidelines for use in real-world contexts at various stages of the product life cycle. It will expand knowledge of the integration of the three factors under study and assist with new studies.

3.8 Step 7: Future work and adaptation path

Step seven marks the end of the proposed framework's cycle; it is linked to the projection of how it can evolve, be tested, and adapted in future contexts. This will allow it to expand its reach and applicability. It is at this stage that the perspectives of empirical validation and integration with new methodological approaches can be realized, along with projecting the continuity of the artifact and indicating how the model can be refined. This definition ensures that the framework remains flexible and relevant in the face of technological and environmental transformations and can be applied to real-world cases and/or simulations, enabling complementary analyses. The proposed framework demonstrates a logical progression from identifying the problem to proposing future improvements. The seven steps correspond to DSR's cycles of relevance, design, and rigor. The objective was to ensure that each phase was designed and developed in an interdependent manner, maintaining methodological coherence and integration among the dimensions that underline the model. The result presents a robust framework that supports decision-making and research on the product life cycle, particularly in the context of sustainable energy systems, with practical applications in real-world settings.

3.9 Framework application

To illustrate the practical application of the framework in academic research, consider a hypothetical interdisciplinary study investigating the sustainable integration of electric vehicles and renewable energy systems. A research team would employ the proposed framework to structure and systematize complex data across multiple dimensions. First, the researchers would map the life cycle of electric vehicles (PLM), documenting technical specifications, supply chain information, operational performance, and end-of-life scenarios. Then, they would integrate this data with e-mobility systems, analysing how vehicle utilization patterns interact with energy consumption and battery performance. Subsequently, the researchers would connect this information to renewable energy infrastructure, examining integration opportunities and potential synergies. Throughout this process, the framework would guide the collection and organization of both quantitative data (e.g., energy flows, efficiency metrics, life cycle assessments) and qualitative data (e.g., stakeholder perspectives, policy frameworks, technological feasibility), allowing researchers to develop a comprehensive understanding of how PLM can support evidence-based decisions on sustainable energy and mobility transitions. This research approach demonstrates how the framework can serve as a methodological tool for structuring complex and multifaceted research problems and supporting the generation of actionable insights for both academic and practical applications. For application of the framework in industry, consider a hypothetical scenario of an electric vehicle manufacturer seeking to optimize the battery lifecycle. Using the proposed framework, the company would first map the battery life cycle data (PLM), from raw material extraction to end-of-life recycling. It would then integrate this data with its e-mobility operations, analysing battery performance and degradation during vehicle use. Finally, it would connect this information to sustainable energy systems, such as the use of second-life batteries for stationary energy storage at solar-powered charging stations. This application would require both quantitative data (e.g., battery degradation rates, energy storage capacity) and qualitative data (e.g., sustainability policies, recycling regulations) to support decision-making and ensure sustainable integration between the three dimensions.

4. Conclusions

Despite its conceptual nature, the proposed framework has applicability as a methodological basis for future studies. The main limitation is the absence of immediate empirical validation, as this study is centered on a conceptual approach. Future research should focus on empirical validation of the framework through case studies in different geographical and organizational contexts. Special attention should be paid to the development of standardized data models and communication protocols that can facilitate interoperability between different PLM systems, energy management platforms, and stakeholder information systems. In addition, research on the economic feasibility of second-life battery applications and the development of circular economy business models around electric vehicle batteries would significantly improve the practical applicability of the proposed framework. Integrating the framework with emerging technologies could further increase its value for decision-making and strategic planning. However, its practical implementation may face challenges, such as the difficulty of data interoperability between different stakeholders (e.g., automakers and energy suppliers), the high costs of implementing integrated PLM systems, and the need for standardized regulations. Therefore, for future research, it is recommended that practical tests be carried out to integrate the studied links. In summary, the framework represents a significant contribution by expanding the possibilities of analysis and integration of the life cycles of electrical products, thus advancing the literature on PLM, electric mobility, and sustainable energy systems.

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