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Reverse salient as a nexus of technologies and values in sociotechnical systems: A case study of lithium-ion batteries

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ABSTRACT

A good comprehension of value dynamics can contribute to a more value-sensitive and responsible design of technology. Theories addressing changes in values related to technology tend to reduce the complexity of technology development, neglecting the intricate interrelations between technical components within sociotechnical systems. This paper proposes an approach that incorporates Thomas Hughes' notion of reverse salient to explore value change across two sociotechnical scenarios, which also aligns with the pragmatic account of values. Through an analysis of the values of safety and sustainability within lithium-ion battery (LiB) technologies, this study illustrates how the approach assesses changes in the relative importance of specific values within a certain domain, as well as the dynamics in the translation of these values. This case demonstrates that the emergence of reverse salients can enhance the recognition of certain values, potentially prompting a reconsideration of how these values are interpreted or translated. The study recommends that future research advances the operationalization of reverse salients and applies them to specific contexts to better manage value change.

1. Introduction

Values can generally be understood as what we believe to be good and desirable [1,2], but such beliefs can change over time due to changing insights or circumstances. The dynamics of values do not only reflect societal evolution, but they are also closely linked to technology development. From the design of specific technical products to the governance of technology, moral values influence how technologies are developed, used, and regulated. In particular, if societal values change, existing social norms and rules that underpin a technology's development may no longer meet the new social demands created by the values of the general public, potentially affecting a technology's social acceptance [3]. By better understanding how values change over time, we can also better anticipate and address the societal impact of technologies. This understanding can help us to design technologies that are more socially responsible and that meet the needs of society over the long term [4].

Philosophers and ethicists of technology have increasingly recognized that values play an important role in co-shaping technology and society. In the latter half of the 20th century, philosophers such as Winner [5] argued that technologies could reflect certain values in the sense that they are sometimes designed to open certain social options and to close others. Moreover, philosophers of technology have, in the past decade or so, further explored the potential for technological development to cause changes in moral values. Swierstra [6], for instance, posited that emerging technologies have the capacity to destabilize established moral norms and values. Other areas of discussion include the technological mediation of moral values [7] and the connection between descriptive and normative value change [4].

Especially, according to a pragmatist account, values are contextually-informed evaluative devices rather than static or intrinsic qualities. This account allows us to view values as emerging from and influenced by experiences and societal interactions [8,9]. As the impact of environmental degradation becomes more severe and widespread, scientists will reassess the value of sustainability. Simultaneously, technologies that appear as solutions to environmental problems might inadvertently foster complacency, reducing the urgency to adopt sustainable behaviors. Alternatively, a more thorough consideration of such technologies can heighten awareness of sustainability issues, prompting more responsible actions and policies [10].

Most theoretical discussions regarding technology-related value change depict a co-evolution of technologies and values, while tending to regard technology as a whole, oversimplifying the diverse nature of technologies and various interconnections between technologies [6,9,11]. Consequently, these explanations tend to adopt a mono-causal perspective, neglecting the intricate interactions and complexities

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between technology and society. However, both value change and technical development are more recursive and complex in social contexts than these theories depict. While the development of technology depends on many distinct technical elements, there are also multiple mechanisms of value change that are potentially interconnected [12]. Based on the interrelatedness of 'social' and 'technical' [13], a sociotechnical perspective has the potential to help us provide a more systematic view of value change. In sociotechnical systems, technological development is the result of the combined effects of diverse elements, inferring each technology influences values not only on its own but also through interactions among technical and social elements. These dynamics collectively contribute to the changes in values. In order to develop a more nuanced approach that acknowledges this complexity, it is important to reexamine the phenomenon within a wider societal framework.

In this paper, the author argues that insights from the notion of reverse salient [14,15] derived from the theory of large technological systems (LTS) can broaden our lens to investigate and explain value change from a sociotechnical perspective. LTS theory highlights the integration and interdependence of technical and social elements, which closely aligns with the theories of sociotechnical systems [16]. Such a sociotechnical viewpoint can facilitate not only a longitudinal analysis of the ongoing evolution of technical systems over an extended period but also an examination of the interplay between value change and technology development, which allows us to develop valuable insights into the complex dynamics of technologies and societies. Moreover, reverse salients are key to technological development, as they hold back progress and development of technological systems, being a source of trouble that forces stakeholders to (re)direct their efforts toward addressing the reverse salient. This paper does not focus on the mono-causal evaluation, but rather places it in the broader sociotechnical context. This approach allows us to understand not only how technological changes in a sociotechnical system can lead to changes in the interpretations of certain values, but also how they could bring about changes in the roles these values play in the system.

To demonstrate this sociotechnical viewpoint, the study will analyze how values have changed in Lithium-ion battery (LiB) technologies from a sociotechnical perspective. As an energy storage technology, LiBs play a crucial role in current energy transitions, which are deeply intertwined with value changes [17,18]. LiBs account for most of the newly installed energy storage capacity and dominate the battery market [19–22]. Due to their successful market uptake and an established industrial value chain, LiBs are likely to remain the dominant battery type until 2030 [19]. Grasping values in technology design can contribute to more effective and equitable regulations and standards, ensuring that technology development is ethical and responsible. The social values related to battery storage technologies seem to have not yet been explored in sufficient detail [23–25], despite their irreplaceable role in the current energy transition. While many studies focus on technical analyses of safety issues and environmental impacts of LiBs [26–28], conceptually examining the specific understanding of values like safety and sustainability is also important. Additionally, learning the dynamism in the understanding of values in LiBs is also beneficial for us to consciously and continuously adjust our design and evaluation schemes.

The following sections will first introduce a socio-technical account of value change based on Hughes' notion of the reverse salient. In particular, the study will explore a practical approach to understanding value change in specific sociotechnical scenarios. Then, it will demonstrate how to account for value change in socio-technical systems by using the development of LiBs as a case study. This will provide a historical overview of LiBs and illustrate their roles in socio-technical systems. In addition, it will demonstrate the intertwined evolution of socio-technical systems and value change. Based on the case analysis, this study will further discuss the role of the reverse salient in explaining the changes in the relationships between technologies and values and in the translations of values.

2. Accounting for value and value change based on Hughes' theory

The work of Thomas Hughes (historian of technology), is an insightful resource for understanding the roles of values in sociotechnical systems [29]. As the body of theoretical discussions on sociotechnical systems is still growing, Hughes's theory is perhaps not the most prevalent recently, but his contribution, as a seminal approach to sociotechnical systems, retains its significance in understanding the intricate relationship among several components in the development of sociotechnical systems. Moreover, his perspective of technical systems still plays an important role in the study of specific technologies, such as infrastructural technologies and energy technologies, which have implications for system transformation and, for example, the energy transition [30,31]. As one of the first scholars to focus on technological systems, Hughes recognized that social factors play a significant role in shaping technological development. Additionally, he argued that technology can have a reciprocal effect on society and that this effect can become increasingly difficult to control as the technical system expands and gains momentum. In a Hughesian history of technology, there is a complex interaction between technology and society [32]. The transformation of social, political, and cultural values could both shape and be shaped by technological change.

Playing an important role in technological change, reverse salients are components that fall behind the others in a growing system, limiting the performance of the system and hampering its evolution. For instance, Hughes identified the direct current (DC) system as a reverse salient in the expansion of electrical networks, noting that DC power can experience significant energy loss when transmitted over extended distances [15]. Another illustrative example is the health concerns arising from polyvinyl chloride (PVC), particularly the carcinogenic properties of vinyl chloride. In these situations, addressing the reverse salients becomes indispensable to developing or expanding the technical system [33]. Despite Hughes not taking a particular interest in values, Hughes's notion of reverse salient provides insight into the connections between technology and values [34]. This section will first briefly analyze the notion of reverse salient before investigating the relationship between technologies and values from Hughes's perspective in detail and discussing how his theory can account for value change.

According to Hughes, reverse salients are determined by the attributes of the system [15]. In other words, they are not random problems but systemic issues within the technology as a goal-seeking system. Hughes emphasizes that the goal and direction of system evolution are particularly significant for young systems, with inventors and engineers playing crucial roles in this goal-seeking process. However, the author points out that even in past technological developments, this process might not have been entirely subjectively determined by inventors and engineers. On the one hand, inventors and engineers themselves are embedded in networks of power and constrained by higher authorities. On the other hand, societal values influence the formation of goals, thereby affecting how technical performance is measured and evaluated. As a technological system progresses towards broadly established goals, reverse salients appear when "some components fall behind [15]."

From Hughes's work, the following four criteria by analyzing reverse salients can be derived. First, a reverse salient implies a discrepancy between the components in a certain sociotechnical system. As Hughes states, reverse salients arise "*in the dynamics of the system during the uneven growth of its components* [15] (p.14)." The discrepancies present as uneven growth, which leads to parts of the system "falling behind" or being "out of phase" with other parts, creating imbalances that hinder the system's overall performance and progress. Second, these discrepancies can negatively impact the performance and development of the system. Hughes points out that "*the reverse salient usually appears as a result of accidents* [15] (p.81)," and consequently, "*growth of the entire enterprise is hampered or thwarted, and thus remedial action is required* [15] (pp.79-81)." These negative impacts often draw attention and can have adverse effects on society, making a technological system incompatible with its external context. Third, reverse salients suggest that these discrepancies and their impacts are persistent issues and not random or transitory. According to Hughes, the laggard components would “remain a reverse salient” if they were not improved. In other words, reverse salients are a persistent challenge requiring effort and adaptation to manage, rather than being random or short-lived phenomena. Fourth, as Hughes emphasized, unlike common technological bottlenecks, a reverse salient demands urgent resolution before it “becomes a radical one [14] (p.69).” Although Hughes describes this resolution process as “a voluntary action,” it is urgent in time and reflects universal societal values. Table 1 lists these four criteria for recognizing reverse salients.

2.1. *Reverse salient as a nexus of technologies and values*

Based on the analysis above, reverse salients refer to persistent discrepancies which negatively impact the development of sociotechnical systems and require timely correction. The discrepancies can arise from a variety of factors, including internal forces, social factors, the natural world, or a combination of these [15]. In order to expand a technological system, system developers need to identify the reverse salients in the system and articulate them into a set of so-called ‘critical problems’, which are *solvable* translations of the reverse salients [15]. Reverse salients can inform technology developers of the crucial issues to secure the success of a new technology, directing the focus of technology developers towards aspects or dimensions that fall short of established normative standards. These standards often reflect certain values, indicating what is considered important and desirable, suggesting that reverse salients *are indicative of, or pertain to*, the values associated with technology in development.

A reverse salient can be regarded as a nexus of technologies and values. When constraints directly shape technology development, the reverse salients in a sociotechnical system may draw attention to specific aspects of values and lead to new perceptions of values, while changes in stakeholders’ values, in turn, may also cause or contribute to the formation of reverse salients. This is in line with a pragmatist understanding of values and value change. According to Dewey [35], values arise only when there is “something the matter” or “trouble” in the current state, indicating a lack or a conflict that disrupts a smooth course of events. This concept aligns closely with the notion of reverse salients, which implies deficiencies or “troubles” in a sociotechnical system. Such troubles cause a tendency to avoid negative issues, which is not merely an instinctual reaction but can also be regarded as the starting point for an evaluative process.

2.2. *A sociotechnical account of value change based on reverse salient*

As lagging components in a technological system, reverse salients are triggers not only for technological advancement but also for evaluative processes. Responding to reverse salients entails new evaluative processes, which may lead to the updating of value systems in sociotechnical contexts. These processes can lead to the scrutiny and even the restructuring of existing value systems, while pre-existing values also influence the way we recognize and address these challenges. Literally, technological development necessitates extensive decision-making. The evolution of technological systems requires recognizing reverse salients and identifying concrete solutions. Developers, users, and stakeholders continuously assess the worth, utility, and desirability of technologies and their features based on various criteria, including efficiency, effectiveness, user satisfaction, and societal impact. All these decision-making processes inherently involve ongoing evaluation influenced by broader social and environmental contexts. Such evaluation is an active and continuous process, which not only relies on pre-existing value systems but also entails a continuous reevaluation of values in light of new information and experiences, possibly resulting in an updated value system.

Table 1
Criteria for recognizing reverse salients.

Criteria	Description
Discrepancy	A reverse salient implies a discrepancy between the components in a sociotechnical system, where some parts fall behind or are out of phase with others.
Impact	These discrepancies negatively impact the system’s performance and development, hindering overall progress.
Persistence	Reverse salients are persistent issues that require continuous effort and adaptation, rather than being random or transitory phenomena.
Imperativeness	They demand urgent resolution to prevent them from becoming more radical problems, reflecting their critical importance and the need for timely intervention.

Instead of separately analyzing the individual factors—such as specific technologies [9,10,36], economic environment [37,38], and public policies [39,40]—that cause value change, this study adopts Hughes’s approach, viewing technology as a system comprising interrelated technical and social elements.[1] In such a system, these factors do not exist independently but are related to the specific context of the system. The different contexts of system development influence evaluation practices, as different decision-making scenarios in sociotechnical system development can lead to different evaluation processes. Consequently, evaluation processes in different sociotechnical situations will have different characteristics, leading to different forms of value change. Focusing on the notion of reverse salients, this study will develop a sociotechnical account that mainly incorporates two scenarios: the recognizing and addressing of reverse salients. In these two scenarios, the different evaluations prompted by reverse salient will also lead to different changes in the value system.

As Fig. 1 shows, when evaluating our instinctive reactions to reverse salients, system developers will judge if these negative issues are undesirable performances, which can not only create an inconvenient situation but also represent a fundamental challenge to the system’s integrity and development. Through this process, pre-existing value systems as evaluative devices are reaffirmed.

Furthermore, these undesirable performances not only reveal the lacks or conflicts but also spur individuals to address the issue further. According to Hughes, addressing reverse salients rests on defining and resolving critical problems. This involves taking the broad challenge of a system’s backwardness and breaking it down into specific, solvable issues that can be addressed by engineers and developers [15]. In response to this undesirable performance, technology inventors and developers recognize and carefully consider the values at stake and make judgments about which aspects of performance are more critical to the system’s success. Translating a reverse salient into specific critical problems involves reflecting on the underlying values that guide the development of the systems, motivating inventors and engineers to analyze the urgent needs or missing elements in the realm of technology.

While the reaffirmation of established value systems can change the priorities of values, the reevaluation of existing values can potentially foster new perceptions of values. In other words, reverse salient are related to not only relationships between technologies and values but also certain translations of values in the sociotechnical systems. In particular, well-publicized technological catastrophes and problems can elicit public reactions and precipitate changes in public attitudes in addition to technical inadequacies [41]. The problems caused by reverse salients incline stakeholders to question and challenge current situations, providing an opportunity for individuals to reflect on the

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[1] While these studies may not explicitly mention value change, they address at least one of the two types introduced earlier: changes in technology-value relationships or in value translation.

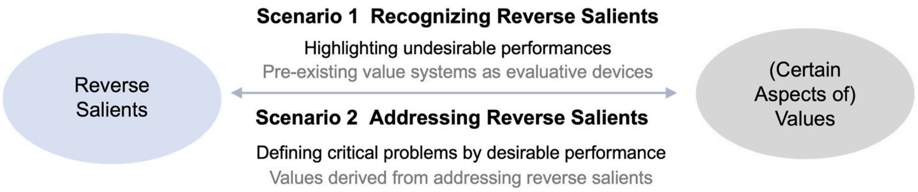

Fig. 1. How reverse salients can relate to values.

underlying value and related normative standards critically and then consider alternative interpretations of values and related standards that may better align with their aspirations and concerns. This reflection can facilitate a more nuanced understanding of the ethical implications of technology and trigger a process of normative reorientation. By addressing the issues highlighted by reverse salients, system developers and actors can expand and refine their value systems, prompting a recalibration of what is and should be valued.

3. A case analysis of LiBs

This section will exemplify how the analytical approach in the above account based on the notion of reverse salient can be used to analyze value change in the specific sociotechnical context of the development of Lithium-ion batteries (LiBs). LiBs are indispensable in the current energy market, and their development demonstrates value dynamism in sociotechnical systems, as this section will show. Widely deployed in consumer electronics, stationary energy storage, and transportation, LiBs are the fastest-growing and most impactful segment in the rechargeable battery market [42–44]. They offer high energy density, low self-discharge rate, fast charging, long lifespan, and no memory effect. While lithium-ion materials' high energy density allows for efficient energy storage, the movement of lithium ions between the cathode and anode via an electrolyte during charge and discharge cycles enables repeated charging without significant capacity loss, making them ideal for consumer electronics, electric cars, and renewable energy systems [45]. Playing a critical role in a fossil fuel-free economy [46], the LiBs industry also raises numerous social and ethical issues with regard to mining, recycling, and safety hazards, but also by affecting the distribution of capital and power [47].

3.1. Methods for case analysis

This case analysis will be a qualitative longitudinal study, spanning from the late 20th century to the early 21st century, on LiBs based on a targeted literature review in which three stages have been identified that concentrate on a specific emphasis on a certain understanding of values connected to the development of LiBs.

The analysis comprises three phases. The first phase is to determine the relevant values for the analysis. There can be many methods to carry out the research in this phase, such as stakeholder interviews [48] and sociotechnical value mapping [49]. However, in this case, the author decided to use a simplified approach by tracing the themes mentioned at major conferences and journals in the field to select representative values as examples for analysis. To find out the relevant values to LiB, the study has reviewed the topics mentioned in the meeting notices and prefaces of the proceedings of the International Meeting on Lithium Batteries (IMLB), which is the most important international conference in the LiB community [50]. If a problem and its impact are frequently mentioned in the literature, it can also be expected to figure as an important reverse salient.

In the second phase, the analysis requires a historic inquiry to grasp the periodization of the technology development. In this case, the author has used "history" and "lithium battery" as keywords to roughly search for research papers that briefly outline the history of LiBs to gain a preliminary understanding of the development history of lithium batteries. The development of LiBs will then be divided into stages based on recognized milestone events and trends.

The next phase involves a conceptual analysis based on the most relevant and important articles for each stage, concerning the values determined in the earlier phases. The most relevant and highly cited reviews from different stages will be selected for reading, and a snowball search will be conducted to investigate and supplement the details. For example, if safety is chosen as the focus, an initial search will be conducted in Web of Science using the query "TS = (Lithium* OR Li-ion* OR Li ion* OR lithium ion* OR lithium-ion* OR LiB*) AND (battery*) AND (safe* OR thermal* OR fire*)." Following the identification of the targeted publications, an analysis is required to examine how these articles interpret the selected values.

While extensively searching for relevant technical reports, media news, and academic papers, the first two phases of the study have particularly focused on two significant journals in the field – the *Journal of Power Sources* and the *Journal of The Electrochemical Society*. These two journals are among the top journals in terms of the number of publications on LiBs and have a relatively long history compared to other newly established top journals in the field. Both journals have published proceedings from important conferences on LiBs, including the IMLB and the Symposium on Lithium Batteries at The Electrochemical Society meeting. This facilitates the tracing of changes in relevant research themes by reviewing the titles and abstracts of relevant studies in the proceedings to understand the characteristics of different stages.

3.2. Values in LiBs

As mentioned above, LiBs technologies, like other technologies, are value-laden. Different LiB technology scenarios may relate to distinct moral values, such as safety, sustainability, and (social) justice [27,28, 51–53]. The ongoing advancements in LiB technologies can drive the evolution of existing technology scenarios and the emergence of new scenarios. While safety has always been a focal point in the evolution of LiBs, the strategies adopted by researchers and engineers to mitigate the risk of fire accidents have continually evolved. Concurrently, sustainability has become increasingly important for LiBs, particularly due to the strain on mineral resources and the pollution caused by challenges in recycling. Besides, the production of LiBs has also begun to challenge other values, such as social justice issues in lithium mining, and potential concerns regarding user privacy in battery management systems, though these topics have received relatively less attention.

Based on the preliminary analysis of focused topics in meetings like IMLB, this case study will mainly focus on the value of safety and sustainability for two reasons. First, issues and concerns about safety and sustainability widely overlap with one another, as they both maintain an emphasis on the protection and development of society (people), the economy, and the environment (ecology) [54]. More specifically, values of safety and sustainability are both deeply intertwined with the overarching goal of hazard reduction, due to the special characteristics of LiBs – thermal instability and reliance on critical metals [55]. Second, safety and sustainability may also be the most discussed moral values in the development of LiBs [26–28], since the challenges of thermal hazard and recycling in LiBs have not only been emphasized in policy documents, but also in academic conferences. In sum, focusing on these two of the most discussed values allows the analysis to center around the core themes and concerns that have historically driven the development of LiB technologies. This provides a more focused and structured approach to exploring the development of LiB technologies across different historical stages. Each stage can be examined through the relationship between the reverse salient and the values, providing a coherent narrative.

3.3. Dynamics of reverse salient in LiB sociotechnical systems

While LiB technologies may not conform to the typical technical system described by Hughes, the theoretical approach presented in section 2 remains applicable to LiB technologies. LiB technologies can be analyzed as technological systems in at least two distinct ways. Firstly, LiB technologies constitute a sociotechnical system that encompasses the entire lifecycle of batteries, including mining raw materials, manufacturing processes, integrating various devices, and recycling or disposal at the end of the battery's life. These technical elements are also intertwined with social elements such as labor practices, policy documents, consumer behavior, and economic trends. Secondly, LiB technologies are integral components of larger sociotechnical systems, such as electric vehicles (EVs), consumer electronics, and stationary energy storage systems. LiBs interact with other technologies, infrastructures, regulations, and user practices in these broader systems, creating a complex web of technical and social dynamics.

From a sociotechnical perspective, the development of LiBs can be divided into three stages, marked by key technological development milestones and trends: early research and experimentation (1970s–1980s), commercialization (1990s–2000s), and expansion into new applications (2010s–now). The first stage began in the 1970s with the commercialization of primary (non-rechargeable) Li-metal batteries. Initially driven by military demands for power sources and the oil crisis [56], all research on LiBs was conducted in laboratories, and the LiB sociotechnical system was still in the making during this period. The early formation of the LiB sociotechnical system characterized the second stage. In 1991, Sony emerged as the pioneer in LiB commercialization, a milestone in the industry, setting the stage for the widespread adoption of LiBs in electronic devices [56–58]. The third stage is marked by the expansion of LiB sociotechnical system in the era of energy transition, especially in new energy storage and electric vehicles, during which the explosion of the electric vehicles industry provided a giant opportunity for the development of LiB [59] and research into LiB had drastically increased [60].

Within the sociotechnical system of LiBs, reverse salients are not static, but rather subject to change, which can also be associated with value change. Referring to system components that lag in and thus impede its progress, reverse salients have shifted as the system expanded and evolved. Once a previously identified reverse salient is addressed within a specific sociotechnical system, it will no longer be considered a reverse salient; conversely, new reverse salients emerge as a sociotechnical system expands and incorporates new elements. Since the various interrelated technologies of LiBs can be regarded as a sociotechnical system, different reverse salients can arise at different stages of their development. The following part will discuss the reverse salients and their relation to the value of safety and sustainability at each stage.

3.3.1. Early research and experimentation (1970s–1980s)

Researchers drove the early research of LiBs by a combination of internal and external factors. Key scientific contributions came from Nobel laureates Stanley Whittingham, who established the principles of intercalation chemistry in the 1970s; John Goodenough, who discovered lithium cobalt oxide ($LiCoO_2$) as a cathode material, enhancing LiB energy density in the 1980s; and Akira Yoshino, who assembled the first modern LiB prototype in 1985 [45,61,62]. Concurrently, external stimuli like the U.S. military's investment in LIBs for lightweight, high-energy applications, the push for alternative energy sources following the 1973 Oil Crisis, and the growing need for advanced medical devices fostered the technology's development [57,63,64].

During this early stage, the secondary LiB system concentrated on rechargeability, with thermal stability also being a key concern [65,66]. Researchers were primarily concerned with finding electrode materials and electrolytes that would not pose risks by their nature. They tried methods such as purifying the electrolyte, using surface modifiers, and employing alloying substrates [67]. Specifically, intercalation was recognized as a method to form stable compounds, thereby reducing the risk of unwanted reactions or depositions [68]. Concerns about sustainability were not pronounced, as the immediate goal was to establish a reliable and safe battery. According to papers in the *Journals of Power Sources* and *Journals of Electrochemistry*, researchers tried to find more stable electrolytes and electrode materials [69]. This was not easy, and some companies even gave up developing LiBs because they were too unstable. For example, in the 1980s, Exxon discontinued its investment in LiB research, not only because of the resolution of the oil crisis, which had initially motivated Exxon's investment, but also due to the company's lack of confidence in the application potential of LiBs, which were seen as unstable and prone to fire [70]. Similar to rechargeability, the safety of LiB was directly linked to their performances. In the absence of safety, their application would not be possible.

Additionally, the acceptance of hazards was very low in the early days of LiBs. Evidence highlighting the focus on inherently safe materials during that period can be gleaned from news reports. For instance, a case in point is the incident involving the battery pack of a cellular phone by Nippon Telephone and Telegraph in August 1989 [71,72], which led to consumer apprehension. While the battery's combustion caused only minor injuries to its users, it spelt an unwanted financial disaster for battery manufacturers. The epic story of Moli Energy exemplifies a case of a reverse salient, where a hazardous battery malfunction in a cell phone triggered a recall and highlighted the requirement for safety [73]. This incident propelled the critical issue of lithium-metal's volatility in batteries to the forefront. The revelation that lithium-metal was ill-suited for the recharge cycles of personal electronics fundamentally challenged the industry's unwavering belief in the material's safety, prompting a reassessment of value specifications.

Even though researchers did not frame the problem of thermal instability as a safety issue from the beginning, there was a strong emphasis on inbuilt safety features in the early stage of LiB development, making thermal stability a reverse salient in this stage. This focus was driven by several factors, including the immaturity of the technology, the need to establish a reliable and safe foundation, and the high stakes associated with battery failure. This resulted in the development of more stable electrolytes and electrode materials, as well as the adoption of design features that could mitigate the effects of accidents. The importance of safety was further underscored by high-profile incidents such as the Moli Energy battery recall.

3.3.2. Commercialization (1990s–2000s)

The commercialization of LiBs began in the early 1990s with the introduction of the first commercial LiB by Sony. The first commercial LiB was a nickel-cobalt-aluminum battery which had a capacity of 1.2Ah and was used in the Sony Mavica digital camera [74,75]. This was followed by the development of LiBs by other companies, such as Panasonic, Sanyo, and LG Chem [76,77]. The commercialization of LiBs led to a growing market, as they were used in a wide range of applications, including consumer electronics, electric vehicles, and energy storage systems. By the end of the 1990s, LiBs were being used in a variety of consumer electronics products, including laptops, camcorders, and mobile phones [69,78].

In the early days of LiB development, the effort to search for safer materials led to significant advances in the development of LiB materials and electrolytes. Researchers identified and prioritized the use of materials that were less likely to pose risks, even in the event of failure. This resulted in the development of more stable electrolytes and electrode materials, as well as the adoption of design features that could mitigate the effects of accidents. In this period, inventors began to focus on designs beyond the basic battery components—designs that do not impact the fundamental functions of the battery but can enhance its safety performance. For example, some researchers started to work on packaging technologies that isolate cells, focusing on the use of non-flammable components that could avoid unintended reactions within the battery pack, thus preventing explosions in use and transportation [79]. The incorporation of safety vents in packaging could also prevent explosions by releasing pressure in a controlled manner [80,81]. As technical challenges related to thermal instability were partly overcome, safety issues became less pressing, although they have persisted in garnering attention.

The issue of resource supply began to surface, highlighted by the limited availability and unequal distribution of critical minerals like lithium and cobalt. The reverse salients at this stage were characterized by unwelcome price fluctuations and worries about mineral depletion, prompting strategies to explore new mining areas and search for new, cheaper materials to ensure the continued growth of the LiB market. As the technical challenges related to safety were gradually solved, the system faced new limitations, including resource scarcity and the economic implications of material sourcing. This shift reflects a broader understanding of the implications of LiB technologies beyond immediate technical concerns. The partial addressing of safety concerns facilitated commercialization of LiBs, but also highlighted the problem of resource scarcity. Therefore, while the instability of LiBs remains a reverse salient, the sustainability of resource supply has also become a significant issue. The growing awareness of sustainability issues continued to shape the development of LiB technology in the next stage.

3.3.3. *Expansion to new applications (2010s–now)*

The rising frequency of climate disasters has made it increasingly important to advance the energy transition, which fosters the environment for the expansion of LiBs into new applications, especially EVs and large-scale energy storage. Beginning in the early 2010s, the escalating demand for EVs and energy storage systems resulted in the expanded production and size of LiBs. In 2010, Tesla, the leading EV company, secured a $465 million loan from the US Department of Energy and repaid it nine years early. It rapidly became California's largest auto industry employer and gained wide acclaim for its products [82]. Before 2010, electric vehicles were largely marginal, almost prototype products, but sales surged rapidly from 2010. The global electric car stock reached 1 million units in 2015, grew to 2 million by 2016, and reached 7.2 million by 2019 [83]. During the same period, LiBs have also been integrated into the electricity grid to stabilize intermittent renewable energy supply. An increasing number of LiB-related applications have emerged, aiming to decarbonize transportation systems and expand renewable energy usage [84,85].

Due to the current electrification and decarbonization of society, energy technology, as a decisive factor in modern society, faces increasingly stringent and complex requirements, further highlighting the issue of thermal stability in LiBs. Firstly, the growth in LiB applications has led to an increase in the number of accidents. These batteries are ubiquitous in our daily lives, from powering various electronic products and transportation systems to facilitating large-scale energy storage in solar and wind power plants. Secondly, the scale and intensity of LiB accidents have also increased due to the rising energy capacity and the growing energy density. In the early 1990s, a LiB of less than 10 Wh was adequate to power Sony CCD-TR Series camcorders [86]. Post-2010, the average LiB capacity in EVs rose to 40 kWh, and by the late 2010s, grid-scale storage demanded LiBs with capacities ranging from tens to hundreds of MWh. The energy density of LiBs has also risen from 80 Wh/kg in the 1990s to more than 400 Wh/kg by the end of the 2010s [87]. With increased energy density, even simple damage can release substantial heat. Furthermore, accidents are showing greater diversity in their details, not only due to the increasing variety of application scenarios but also because of growing attention to technical aspects like transportation and recycling.

As a major manifestation of the thermal instability of LiBs, LiB accidents have not only forced technical personnel in the field to pay more attention to improving the safety of LiBs but also made the public more aware of the safety issues of LiBs. As a result, the importance of safety in the LiB sociotechnical system has increased significantly since the 2010s, as LiB accidents have become more frequent and severe [88,89]. However, the concern of safety is not only limited to prioritizing safety in LiB technologies, but also encompasses the respecification of safety in LiB standards. For example, the application of LIBs in electric vehicles (EVs) has increased the demand for impact resistance, as traffic accidents can easily cause mechanical harm, which in turn might trigger thermal hazards in LiBs, exacerbating the situation. In addition to the conventional tests for thermal heating and (dis/over)charging, standards such as IEC 62660-2 have included tests for dropping and vibration [90]. In addition, as the capacity of battery packs increases, the emergence of Battery Management Systems (BMS) has begun to play a more proactive role in accident prevention through temperature monitoring as well as State of Charge and State of Health monitoring [91].

In the same period, the issue of raw material availability also became more pressing with the scaling up of LiB production. While instability in raw material supply, leading to price instability and difficulty in reducing costs, was already a concern in the previous phase, the scarcity of raw materials has now led our world to face a shortage, particularly of lithium and cobalt [92,93]. Moreover, the environmental damage caused by LiB production, particularly the mining process, has also gradually attracted attention. Since LiB materials are not highly toxic, research on the environmental impact of LiBs is mainly focused on aspects such as greenhouse gas emissions during production. The undesired impact of raw material extraction, such as lithium mining, on local ecosystems is also becoming increasingly evident. In addition to environmental damage, mining can sometimes have negative social impacts [94,95]. In some cases, mining activities have the potential to result in the displacement of local populations or adversely affect their health and well-being.

As the looming raw material shortage and the environmental impact of LiBs came under scrutiny, the sustainability of the LiB industry has also gained increasing attention. Addressing these challenges is crucial not only for the LiB industry but also for other sectors reliant on stable battery supplies; whilst noting that the sustainability of the LiB industry is multifaceted, encompassing environmental, social, and logistical challenges at every stage of its life cycle [27,96,97]. Stakeholders in the industry are trying to address the sustainability challenges of the LiB industry through various strategies. During this phase, an increasing number of researchers started focusing on more efficient and safe LiB recycling methods. Policymakers also have made efforts to address the issues of lithium and cobalt mining and set recycling requirements for LiB companies. Additionally, academia has kept exploring alternative energy storage methods like sodium batteries and aqueous zinc-ion batteries. In this context, the importance of sustainability in LiB technology has grown, and the specification of sustainability has become increasingly diverse, sometimes even leading to conflicting interpretations. The supply chain issue, initially focused on whether natural resources could continuously support LiB production, has now extended to include concerns about whether LiB production can avoid negative environmental and social impacts. At this stage, as the problem of battery stability intensifies into a severe reverse salient, the supply of raw materials also becomes a serious issue that requires proper resolution.

4. An interpretation of value dynamism in the LiB development

As summarized in Table 2, the emphasized aspects of values have continuously changed over time, with the relative importance and interpretation of safety and sustainability undergoing changes through

Table 2
A summary of the case analysis on LiBs.

Development Stage	Reverse Salient	Critical Problems	Emphasized (Aspects of) Values
Early Research and Experimentation (1970s–1980s)	The instability as a flaw in LiBs, leading to the discontinuation of LiB development by companies like Exxon	What materials can demonstrate resilience to overheating, thermal runaway, and explosive reactions?	Initial focus on inherent safety, leading to the search for stable electrolytes and eletrodes
Commercialization (1990s–2000s)	Despite improvements, thermal stability still requires certain attention	What methods can reduce the occurrence of accidents involving electronic products and incidents in industrial production?	Shift towards more extrinsic safety measures in production and transportation processes
	Resource supply concerns due to price fluctuation and mineral depletion	How can the dependency on precious metals in product manufacturing be reduced?	Focus on the sustainable growth of the industry
Expansion into New Applications (2010s–now)	The growing scale and density of batteries highlight the persistent issue of thermal stability	What are more effective strategies for addressing increasingly frequent and severe incidents?	More proactive measures to address safety, enhanced safety standards and practices
	Challenging extraction of raw materials that are unevenly distributed and limited in availability	How can the impact of lithium battery production on local communities and the environment be mitigated?	Intensified commitment to sustainability, leading to increased industry focus on efficient recycling methods and alternative energy storage solutions

the different stages of LiB development.

a) Safety

In the development of lithium-ion batteries, safety remains a paramount concern. The understanding of safety has undergone two key transformations. The first shift moved from an emphasis on what can be called inherent safety to extrinsic safety. Here, “inherent safety” refers to the intrinsic stability of a material or design that minimizes risks by its very nature, reducing the need for additional safety strategies. In contrast, “extrinsic safety” emphasizes the addition of protective measures. While not essential to the battery’s primary operation, these measures provide further safety by managing and containing the effects of potential failures. The second shift saw an expansion from passive to active safety. “Passive safety” relies on design features that passively protect users and minimize injury without requiring any preemptive action or intervention. Conversely, “active safety” incorporates features that actively prevent accidents and enhance the battery’s operational safety by helping prevent hazards and maintain control (see Fig. 2).

The initial two stages of LiB research were characterized by a passive safety approach, which involved rigorous testing and examination of sample products to minimize the consequences of potential incidents. As thermal instability presented a significant challenge from the very beginning, researchers tried to find inherently safe electrode and electrolyte materials—those with properties designed to mitigate the reactivity of lithium electrodes without the need for additional safety measures. In the second stage, safety issues were resolved to a certain extent, as researchers and engineers found relatively stable lithium intercalation compounds [98], which were inherently safer. Therefore, researchers expanded their focus in this period to design beyond the fundamental components of the batteries, particularly battery packaging [79]. This shift marked a move towards a more extrinsic interpretation of safety, involving additional measures outside the battery’s core design to bolster safety. Such extrinsic safety features, while not integral to the basic functioning of the battery, serve to supplement safety by providing additional layers of protection, such as robust casings to contain and manage the effects of potential failures.

After 2010, with the increased performance demands on LiBs, more active safety strategies have been developed. These measures are characterized by systems added onto the battery to monitor actively and control operational conditions, such as temperature, voltage, and current, thereby preventing unsafe scenarios. This evolution represents a philosophical transition in LiB safety strategies from reliance on inherent safety—safety embedded within the basic design, obviating the need for extra devices or procedures—to a combination of passive and extrinsic active safety. The latter involves additional systems external to the core design, implemented to mitigate risks further and enhance the battery’s operational safety.

b) Sustainability

Sustainability was not prioritized in LiB design at the beginning as LiBs were thought to be much greener than traditional batteries, which relied on heavy metals. However, after the commercialization of LiBs, the issue of raw material supply emerged. Due to local resource depletion, unequal resource distribution, and other issues, the industry began to worry about the stable supply of natural resources. In the 2010s, with the emergence of new applications, demand for raw materials skyrocketed, and accompanying social and environmental issues also increased, such as the impact of mining on local ecosystems. The interpretation of sustainability has undergone a significant shift, moving away from the industry-oriented “weak sustainability” approach towards a more nature-oriented “strong sustainability” paradigm, which prioritizes the minimization of environmental and social repercussions (see Fig. 3).

Based on the analysis above, the relative importance and interpretation of safety and sustainability within Li-ion battery (LiB) sociotechnical systems have changed. Here, the study distinguishes between two fundamental aspects of value change (also see Ref. [2]).

1) Changes in the relationship between technology and values. This type of value change occurs when the perceived relevance or importance of a value changes within a sociotechnical system.
2) Changes in the translation of values. This type of value change occurs when the way in which a value is understood or operationalized changes.

The approach to managing reverse salients involves two steps (see Table 3) The first step is to *recognize* the reverse salients, and the second is to *translate* them into critical problems. In the first step, established values serve as evaluative devices to assess the performance of technological systems. When undesirable performances are identified and capture attention, developers (re) affirm the importance of corresponding established values that have not been successfully embedded, which may change these values’ priority in the design process. This process functions as an evaluative judgment that questions the system’s alignment with established values, essentially asking: “Does the current state of the system adhere to established values?” If the answer is “yes”,

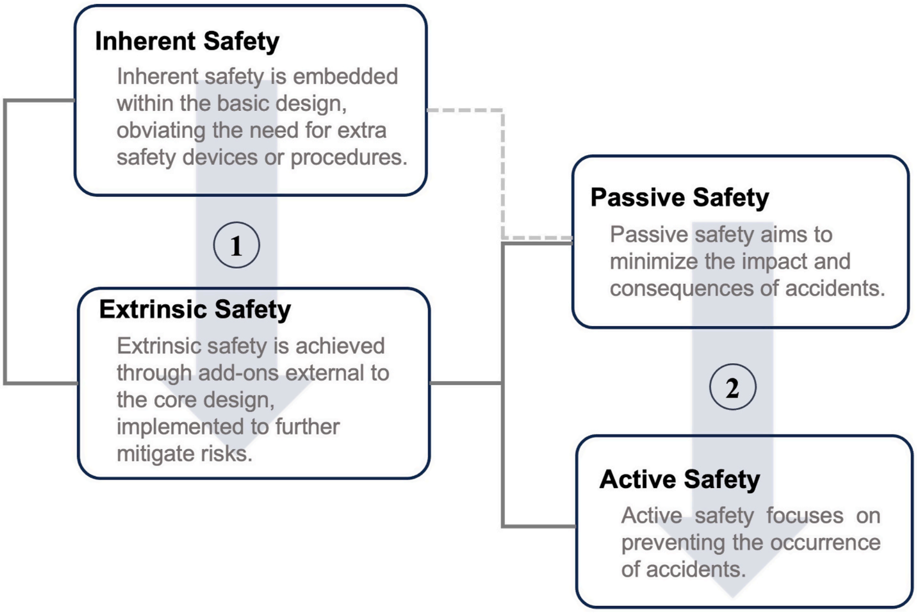

Fig. 2. The shifting focus of LiB safety.

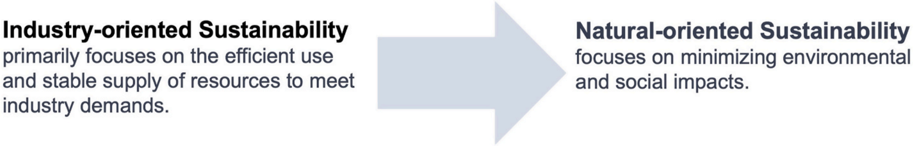

Fig. 3. The Shifting focus of LiB Sustainability.

Table 3
Sociotechnical account of Value Change based on the notion of reverse salient.

Technical system development	Evaluation processes	Types of value change
Reverse Salients represented as undesirable performance	Pre-existing values are reaffirmed by highlighting undesirable performance	Changes in the relationship between values and technologies
Critical Problem defined by desirable performance	Values are reconsidered in the process of defining critical problems	Changes in the translation of the values

but the feeling of undesired performance persists, developers must consider whether to change the priority of values or incorporate additional values to evaluate the current status. Such recognition of reverse salients relies on an understanding of the existing “orders of worth” or value systems within a sociotechnical context [99].

In the second step, to address the reverse salients, developers must translate them into more specific “critical problems”. The urgency of resolving the problems posed by reverse salients drives developers to engage with these issues further and deliberate on what is considered desirable performance. This reflection is integral to continuously identifying concrete critical problems that demand resolution. Articulating desirable performance and critical problems necessitates the (re) consideration of value translation, which is not limited to discerning what is or should be valued but also how it should be operationalized. The value judgments involved in articulating desirable performance and critical problems can lead to changes in value interpretation, questioning: “How should specific system issues be resolved to better embody and fulfil our existing values?” The questions explored in this stage are more open-ended than those in the previous stage.

5. Discussion

The approach based on reverse salient outlined in Section 2.2 has shown that different sociotechnical scenarios can contribute to different types of value change, which prompts the further examination of the roles of value judgment in recognizing reverse salients and identifying critical problems. This paper asserts technological development and value dynamism are interconnected and mutually influence each other through reverse salients. By such a reverse-salient-based approach, it is possible to explain how reverse salients impact value judgment, leading to value change, and how value dynamism arises within sociotechnical systems. This section aims to deliberate on this mechanism, analyzing how the evolution of sociotechnical systems influences this mechanism and its characteristics.

Within a certain sociotechnical system, the factors influencing the mechanisms of value change described in a reverse-salient-based account appear on two levels: the dynamics of reverse salients and the dynamics of critical problems. At the level of reverse salients, system developers would use commonly acknowledged values to identify the problem better, so certain values will be emphasized if something that is commonly valued is not realized. In an evolving sociotechnical system, reverse salients continuously change; as past reverse salients are resolved, new ones emerge. A given sociotechnical system may face different reverse salients at various stages of development, thus drawing attention to different values at each stage. When a reverse salient persists, its manifestations can vary as the conditions shift, influenced by changes in both the environment and other system components. For instance, the instability of lithium batteries manifests differently in various application contexts. For the same reverse salient, critical problems identified may also change over time, which can be reflected in different translations of values. This dynamic indicates that as stakeholders’ understanding of a reverse salient deepens or evolves, the way in which values are conceptualized and specified—referred to as "translations of values"—also changes.

Furthermore, the relationship between reverse salients, critical problems, and values is not one-to-one. Values associated with a reverse salient may shift, resulting in a scenario where a single reverse salient correlates with multiple values. In the case of LiBs, as the scale of fires increases, the environmental damage caused by such fires raises concerns about environmental sustainability. As reverse salients change, critical problems will change accordingly; however, the converse is not always true. For the same LiB thermal hazard, the critical problem may shift with the social context and the identity of decision-makers, thereby affecting the specification of values in technical texts and policy documents. Similarly, like reverse salients, the relationship between critical problems and values is not one-to-one.

The account presented in this paper is compatible with other theories of value stemming from pragmatism. For example, the destabilizing conditions created by reverse salients are similar to Dewey's "indeterminate situations," which are ambiguous, conflicted, and lack a clear course of action, necessitating an inquiry process [9,35,100]. The notion of reverse salients can further elucidate why technological development can lead to undesirable scenarios as new indeterminate situations. Triggered by unforeseen reverse salients, these undesirable scenarios necessitate a response. This reverse-salient-based account reveals that technical components may not be the sole disruptors, as indeterminate situations arise from the combined influence of all components within the system.

Such an account also explains that the degree of indeterminacy can vary across different situations. Since reverse salients are persistent problems, some destabilizing conditions caused by reverse salients can be recurrent or even predictable. Each occurrence compels a deeper consideration of the pertinent values through which the values used for judgment are recognized and enhanced. In such situations, the challenges or disturbances caused by reverse salients are more determinate and can be resolved through a more direct and intuitive judgment process, not requiring extensive inquiry [99]. When facing new destabilizing conditions, there are at least three possible scenarios for the established value system within the sociotechnical system regarding the relationship between the values and technologies and the translation of these values.

1) The established value system is sufficient for judgment and does not require incorporating new values, changing priorities, or adjusting specific translations of these values.
2) The established value system is adequate for the initial judgment but requires adjustments to the translations of these values.
3) The established value system is insufficient for the initial judgment, necessitating the incorporation of new values or changing priorities, and corresponding adjustments to the translations of these values.

As evaluation devices, value systems can be not only updated but also reinforced during the evaluation process. This reinforcement may not cause a radical shift in priorities, but its cumulative effect can strengthen the relationship between the values and the technology. Whether they align with established values, the focus on these values makes them more relevant to a certain technology. As Wilson and Sperber stated [101], new information can achieve relevance by either strengthening or contradicting an existing belief. In recognizing a reverse salient, value judgments also reinforce established values by highlighting how a part of the system is not meeting the standards or expectations set by them. Identifying a critical problem presupposes the importance of that value within the sociotechnical system, even if it does not imply a change in priority.

Based on the aforementioned theoretical contributions, this reverse-salient-based account is helpful in understanding and elaborating the dynamic connection between technological development and value dynamism within sociotechnical systems. The case study of LiB has practically demonstrated how it can help analyze the phenomenon of value change in LiB sociotechnical systems. Specifically, it can triangulate some phenomena and findings described in other studies on LiB technological development trends. For example, some researchers conducted bibliometric analyses of articles in the field of LiB, showing that research on thermal hazards and safety-related issues in the LiB field rose slowly or even fluctuated from 2000 to 2010 [102,103]. This corresponds to the second phase defined in this study, where safety-related reverse salients were partly addressed. Analyzing changes in term occurrence frequency also reflects a shift in research themes from the electrochemical properties of materials to thermal management, indicating a conceptual transition from passive safety to active safety [104]. The rise of topics like LiB recovery and recycling also correlates with the increasing prominence of sustainability-related problems [104]. This demonstrates that this approach can help explain quantitative research results and even form hypotheses for further quantitative studies.

6. Conclusions

This paper argued that Thomas Hughes's notion of reverse salient can be used to better understand value change in the development of a sociotechnical system. It developed a sociotechnical account of value change based on Hughes's notion of the reverse salient. A case study of the LiB sociotechnical system was conducted to demonstrate the initial perspective, showing how reverse salients may be connected to values. By spotlighting the gap between the actual and desirable performance, the formulation and resolution of a reverse salient has the potential to draw attention to certain values or certain translations of values. The study further elaborates on how this approach can be applied to elucidate changes in values: generally, both reverse salients and critical problems vary according to the specific context; therefore, in diverse scenarios, different aspects of value are recognized and weighed during deliberations as people assess the current state, define long-term visions, and identify problems to be resolved, leading to a dynamism of values.

This account presents an analysis of how values relate to and are transformed by technological development, distinguishing and elucidating two types of value change: 1) changes in the relationship between values and technologies and 2) changes in the translation of values. Generally speaking, the latter occurs more frequently on a shorter time scale, while the former spans a broader, more macroscopic frame. This account offers not only an approach for analyzing value change informed by sociotechnical system theories emphasizing interconnections between social and technical elements, but also a linkage between different types of value change through the process of addressing reverse salients. This theoretical perspective also offers insights for responsibly developing technology, encouraging a more active participation in the co-evolution of technology and values.

Aiming to explore the link between reverse salients and value dynamics, this study analyzes their core characteristics and investigates value change within two distinct scenarios of responding to reverse salients. Accompanied by undesirable negative effects, reverse salient is regarded as an inherent defect of a technological system. If a reverse salient cannot be resolved, it will continually be represented as various negative events, thereby causing persistent adverse impacts. Therefore, a negative event always necessitates serious reflection on its causes, requiring us not to compromise our core values. It is crucial for technology developers to responsibly identify the corresponding critical problems and timely adjust the technical specifications as needed. By addressing value change, raising the threshold for technical standards and technological innovation, and being more cautious in the process of technology promotion, the negative impact of reverse salients can be kept within acceptable limits.

This study also offers helpful insights into addressing value change. First, value change can be more complex than anticipated, as many reverse salients are unpredictable. As Hughes mentioned, recognizing reverse salients requires monitoring technological development [14].

While continuous monitoring is currently essential to respond promptly to changes, predicting value change and reverse salients warrants further investigation. Second, value change is highly contextual. To provide guidance on technical details and more practical implications, this approach can be applied to analyze more specific application scenarios in future research. Value priorities and translations may vary across contexts for technologies with broad applications, like LiBs. For example, while safety is crucial in all scenarios, grid energy storage does not prioritize space efficiency—i.e. energy density—as much as electric vehicles do.

Admittedly, the concept of reverse salient has not been given a strictly operational definition, although it has significant importance in technological research as a seminal concept related to sociotechnical systems. Reverse salients are highly context-dependent, which can make it challenging to apply a standardized approach to identifying and addressing them. This has resulted in their theoretical significance outweighing their practical value. To better apply it in practice, on the one hand, the definition of reverse salients can be interpreted in a more operational manner by incorporating new methods, such as expert interviews and performance gap measures, to guide technological development [105,106]. This study also proposed criteria for recognizing reverse salients, but further research is needed to standardize these criteria. On the other hand, since Hughes emphasized that reverse salients can be comparable with concepts like bottlenecks [14], other related concepts and identification methods can be referenced to make them more operational. For example, bottleneck technologies, which limit at least one system function, can be identified with the Constraints Approach [107], and system efficiency metrics can reveal critical disparities [108].

Furthermore, this study also lays the groundwork for analyzing value changes from historical and sociological perspectives. On the one hand, through Hughes's theory, the account connects value change with the history of technology; on the other hand, the emergence of reverse salients and the identification of critical problems are not only related to the inherent characteristics of the technology, but also depend on the social environment and actors, which can be further explored from the perspectives of social structure and interaction. This reverse-salient-based approach can serve as an entry point to explore the micro-social processes involved in addressing reverse salients. While individual leading developers play a major role, reverse salients are, in fact, a collective phenomenon influenced by power structures. This approach allows more detailed empirical investigation, which can potentially deepen our understanding of how individual and collective values interact within the web of social power in the emergence and resolution of reverse salients, thereby refining the mechanism of value change. Such a nuanced comprehension of value change, in turn, enables us to recognize the specific process of value change, allowing developers and stakeholders to engage more proactively in the development of sociotechnical systems.

Declaration of competing interest

No conflict of interest exists.

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References

[1] S.H. Schwartz, An overview of the Schwartz theory of basic values, Online Readings in Psychology and Culture 2 (2012), https://doi.org/10.9707/2307-0919.1116.

[2] I. van de Poel, Design for value change, Ethics Inf. Technol. 23 (2021) 27–31, https://doi.org/10.1007/s10676-018-9461-9.

[3] C. Milchram, G. van de Kaa, N. Doorn, R. Künneke, Moral values as factors for social acceptance of Smart grid technologies, Sustainability 10 (2018) 2703, https://doi.org/10.3390/su10082703.

[4] I. van de Poel, Understanding value change, Prometheus 38 (2022), https://doi.org/10.13169/prometheus.38.1.0007.

[5] L. Winner, Do Artifacts have politics? Daedalus (Modern Technology: Problem Or Opportunity?) 109 (1980) 121–136. https://www.jstor.org/stable/20024652. (Accessed 17 March 2024).

[6] T. Swierstra, Nanotechnology and Technomoral Change, vol. XV, Etica & Politica/Ethics & Politics, XV, 2013, pp. 200–219. https://sites.units.it/etica/2013_1/SWIERSTRA.pdf. (Accessed 14 March 2024).

[7] P.-P. Verbeek, Toward a theory of technological mediation: a Program for Postphenomenological research', in: R.P. Crease, J. Kyrre Berg Olsen Friis (Eds.), Technoscience and Postphenomenology: the Manhattan Papers, Lexington Books, London, 2016, pp. 189–204. https://ris.utwente.nl/ws/portalfiles/portal/21754033/theory_of_mediation.pdf. (Accessed 14 March 2024).

[8] N. Heinich, A pragmatic Redefinition of value(s): toward a general Model of valuation, Theory Cult Soc 37 (2020) 75–94, https://doi.org/10.1177/0263276420915993.

[9] I. van de Poel, O. Kudina, Understanding technology-Induced value change: a pragmatist proposal, Philos Technol 35 (2022) 40, https://doi.org/10.1007/s13347-022-00520-8.

[10] B. Hofbauer, Techno-moral change through solar geoengineering: how geoengineering challenges sustainability, Prometheus 38 (2022), https://doi.org/10.13169/prometheus.38.1.0082.

[11] J.K.G. Hopster, C. Arora, C. Blunden, C. Eriksen, L.E. Frank, J.S. Hermann, M.B.O. T. Klenk, E.R.H. O'Neill, S. Steinert, Pistols, pills, pork and ploughs: the structure of technomoral revolutions, Inquiry (2022) 1–33, https://doi.org/10.1080/0020174X.2022.2090434.

[12] J. Danaher, H.S. Sætra, Mechanisms of Techno-moral change: a Taxonomy and overview, Ethical Theory & Moral Pract. 26 (2023) 763–784, https://doi.org/10.1007/s10677-023-10397-x.

[13] G.H. Walker, N.A. Stanton, P.M. Salmon, D.P. Jenkins, A review of sociotechnical systems theory: a classic concept for new command and control paradigms, Theor. Issues Ergon. Sci. 9 (2008) 479–499, https://doi.org/10.1080/14639220701635470.

[14] T.P. Hughes, The evolution of large technological systems, in: W.E. Bijker, T. P. Hughes, T. Pinch (Eds.), The Social Construction of Technological Systems, Anniversary Edition, MIT Press, London, 2012, pp. 45–76.

[15] T.P. Hughes, Networks of Power: Electrification in Western Society, 1880-1930, Johns Hopkins University Press, 1983, https://doi.org/10.56021/9780801828737.

[16] B. Joerges, Large technical systems: concepts and issues, in: R. Mayntz, T. P. Hughes (Eds.), The Development of Large Technical Systems, Routledge, 2019, https://doi.org/10.4324/9780429309991.

[17] A. Melnyk, H. Cox, A. Ghorbani, T. Hoppe, Value dynamics in energy democracy: an exploration of community energy initiatives, Energy Res Soc Sci 102 (2023) 103163, https://doi.org/10.1016/j.erss.2023.103163.

[18] A. Correljé, U. Pesch, E. Cuppen, Understanding value change in the energy transition: exploring the perspective of original Institutional economics, Sci. Eng. Ethics 28 (2022) 55, https://doi.org/10.1007/s11948-022-00403-3.

[19] S. Wolf, M. Lüken, Future battery market, in: Emerging Battery Technologies to Boost the Clean Energy Transition, 2024, pp. 103–118, https://doi.org/10.1007/978-3-031-48359-2_7.

[20] H. Bajolle, M. Lagadic, N. Louvet, The future of lithium-ion batteries: exploring expert conceptions, market trends, and price scenarios, Energy Res Soc Sci 93 (2022) 102850, https://doi.org/10.1016/j.erss.2022.102850.

[21] W. Bernhart, Challenges and Opportunities in lithium-ion battery supply, in: Future Lithium-Ion Batteries, The Royal Society of Chemistry, 2019, pp. 316–334, https://doi.org/10.1039/9781788016124-00316.

[22] Y. Zhao, O. Pohl, A.I. Bhatt, G.E. Collis, P.J. Mahon, T. Rüther, A.F. Hollenkamp, A review on battery market trends, second-life Reuse, and recycling, Sustainable Chemistry 2 (2021) 167–205, https://doi.org/10.3390/suschem2010011.

[23] A.R. Dehghani-Sanij, E. Tharumalingam, M.B. Dusseault, R. Fraser, Study of energy storage systems and environmental challenges of batteries, Renew. Sustain. Energy Rev. 104 (2019) 192–208, https://doi.org/10.1016/j.rser.2019.01.023.

[24] C. Thies, K. Kieckhäfer, T.S. Spengler, M.S. Sodhi, Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries, Procedia CIRP 80 (2019) 292–297, https://doi.org/10.1016/j.procir.2018.12.009.

[25] Z. Chen, A. Yildizbasi, Y. Wang, J. Sarkis, Safety in lithium-ion battery circularity activities: a framework and evaluation methodology, Resour. Conserv. Recycl. 193 (2023) 106962, https://doi.org/10.1016/j.resconrec.2023.106962.

[26] Y. Chen, Y. Kang, Y. Zhao, L. Wang, J. Liu, Y. Li, Z. Liang, X. He, X. Li, N. Tavajohi, B. Li, A review of lithium-ion battery safety concerns: the issues, strategies, and testing standards, J. Energy Chem. 59 (2021) 83–99, https://doi.org/10.1016/j.jechem.2020.10.017.

[27] Y. Yang, E.G. Okonkwo, G. Huang, S. Xu, W. Sun, Y. He, On the sustainability of lithium ion battery industry – a review and perspective, Energy Storage Mater. 36 (2021) 186–212, https://doi.org/10.1016/j.ensm.2020.12.019.

[28] A. Mauger, C.M. Julien, Critical review on lithium-ion batteries: are they safe? Sustainable? Ionics 23 (2017) 1933–1947, https://doi.org/10.1007/s11581-017-2177-8.

[29] F.W. Geels, Technological Transitions and System Innovations, Edward Elgar Publishing, 2005, https://doi.org/10.4337/9781845424596.

[30] K. Mulder, A. Kaijser, The dynamics of technological systems integration: Water management, electricity supply, railroads and industrialization at the Göta Älv, Technol. Soc. 39 (2014) 88–99, https://doi.org/10.1016/j.techsoc.2013.11.003.

[31] D.J. Hess, B.K. Sovacool, Sociotechnical matters: reviewing and integrating science and technology studies with energy social science, Energy Res Soc Sci 65 (2020) 101462, https://doi.org/10.1016/j.erss.2020.101462.

[32] T.P. Hughes, The Seamless web: technology, science, Etcetera, Etcetera, Soc. Stud. Sci. 16 (1986) 281–292, https://doi.org/10.1177/0306312786016002004.

[33] K. Mulder, M. Knot, PVC plastic: a history of systems development and entrenchment, Technol. Soc. 23 (2001) 265–286, https://doi.org/10.1016/S0160-791X(01)00013-6.

[34] N. Ritchie, K. Lovell, Z. Koretsky, Researching the Decline of Large Socio-Technical Systems using Science and Technology Studies Tools (2024).

[35] J. Dewey, Theory of valuation, in: International Encyclopedia of Unified Science, 1939, pp. vii–67.

[36] J. Danaher, H.S. Sætra, Technology and moral change: the transformation of truth and trust, Ethics Inf. Technol. 24 (2022) 35, https://doi.org/10.1007/s10676-022-09661-y.

[37] R.A. Buchholz, S.B. Rosenthal, Technology and Business: Rethinking the moral Dilemma, J. Bus. Ethics 41 (2002) 45–50, https://doi.org/10.1023/A:1021346021768.

[38] Y. Zhang, F. Yu, Which socio-economic Indicators influence collective Morality? Big data analysis on online Chinese social media, Emerg. Mark. Finance Trade 54 (2018) 792–800, https://doi.org/10.1080/1540496X.2017.1321984.

[39] A.J. Mahardhani, The role of public policy in fostering technological innovation and sustainability, Journal of Contemporary Administration and Management (ADMAN) 1 (2023) 47–53, https://doi.org/10.61100/adman.v1i2.22.

[40] F. Nagle, Government technology policy, social value, and National Competitiveness, SSRN Electron. J. (2019), https://doi.org/10.2139/ssrn.3355486.

[41] T.P. Hughes, American Genesis: A Century of Invention and Technological Enthusiasm, 1870-1970, University of Chicago Press, 2004. https://press.uchicago.edu/ucp/books/book/chicago/A/bo3627102.html. (Accessed 19 March 2024).

[42] Energy storage grand challenge: energy storage market report, 2020. (Accessed 19 March 2024).

[43] Y. Liu, R. Zhang, J. Wang, Y. Wang, Current and future lithium-ion battery manufacturing, iScience 24 (2021) 102332, https://doi.org/10.1016/j.isci.2021.102332.

[44] Battery-based energy storage systems market sees lithium-ion products dominate over 50% of the industry: implications of Mega Trends on Batteries, Newstex Trade & Industry Blogs (2015). (Accessed 19 March 2024).

[45] N.T.M. Balakrishnan, A. Das, N.S. Jishnu, L.R. Raphael, J.D. Joyner, J.-H. Ahn, M. J. Jabeen Fatima, R. Prasanth, The Great history of lithium-ion batteries and an overview on energy storage devices. https://doi.org/10.1007/978-981-15-8844-0_1, 2021.

[46] H. Kawamura, M. LaFleur, K. Iversen, H.W.J. Cheng, Lithium-ion batteries: a pillar for a fossil fuel-free economy?. https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/publication/FTI_July2021.pdf, 2021. (Accessed 13 March 2024).

[47] C. White-Nockleby, Grid-scale batteries and the politics of storage, Soc. Stud. Sci. 52 (2022) 689–709, https://doi.org/10.1177/03063127221109605.

[48] B. Friedman Jr., P.H. Kahn, A. Borning, Value Sensitive Design: Theory and Methods, vol. 2, University of Washington Technical Report, 2002, pp. 1–8.

[49] U. Pesch, Identifying interventions for responsible innovation: the sociotechnical value map, in: R. Rocco, A. Thomas, M. Novas-Feradás (Eds.), Teaching Design for Values: Concepts, Tools & Practices, TU Delft OPEN Publishing, 2022.

[50] D. Aurbach, Introduction to the focus issue related to the 2016 international meeting on lithium batteries, J. Electrochem. Soc. 164 (2017), https://doi.org/10.1149/2.0671701jes. Y1–Y1.

[51] J.M. Turner, Charged: A History of Batteries and Lessons for a Clean Energy Future, University of Washington Press, 2023. https://uwapress.uw.edu/book/9780295752181/charged/. (Accessed 19 March 2024).

[52] Lithium-ion batteries need to be greener and more ethical, Nature 595 (2021), https://doi.org/10.1038/d41586-021-01735-z, 7–7.

[53] A.H. de la Iglesia, F.L. Alejano, A.J.L. Rivero, D.H. de la Iglesia, Ethics of Planned Obsolescence in lithium batteries: environmental and social implications. https://doi.org/10.1007/978-3-031-38344-1_26, 2023.

[54] W. Nawaz, P. Linke, M. Koç, Safety and sustainability nexus: a review and appraisal, J. Clean. Prod. 216 (2019) 74–87, https://doi.org/10.1016/j.jclepro.2019.01.167.

[55] R. Danino-Perraud, The Recycling of Lithium-Ion Batteries: A Strategic Pillar for the European Battery Alliance, Institut Francais Des Relations Internationales, 2020. https://www.ifri.org/sites/default/files/atoms/files/danino_recycling_batteries_2020.pdf. (Accessed 14 March 2024).

[56] M. Winter, B. Barnett, K. Xu, Before Li ion batteries, Chem Rev 118 (2018) 11433–11456, https://doi.org/10.1021/acs.chemrev.8b00422.

[57] B. Scrosati, History of lithium batteries, J. Solid State Electrochem. 15 (2011) 1623–1630, https://doi.org/10.1007/s10008-011-1386-8.

[58] G.E. Blomgren, The development and future of lithium ion batteries, J. Electrochem. Soc. 164 (2017) A5019–A5025, https://doi.org/10.1149/2.0251701jes.

[59] Y. Hu, Y. Yu, K. Huang, L. Wang, Development tendency and future response about the recycling methods of spent lithium-ion batteries based on bibliometrics analysis, J. Energy Storage 27 (2020) 101111, https://doi.org/10.1016/j.est.2019.101111.

[60] A.P.D. da Cruz, Lithium-ion Battery: Evolution of Available Scientific Publications and Future Research Trends, Universidade NOVA de Lisboa, 2023. http://hdl.handle.net/10362/148854. (Accessed 16 March 2024).

[61] Profile of Akira Yoshino, Dr.Eng., and Overview of His Invention of the Lithium-ion Battery, Asahi Kasei (n.d). https://www.asahi-kasei.com/asahikasei-brands/interview/yoshino/profile/pdf/lithium-ion_battery.pdf (accessed March 16, 2024).

[62] K. Grandin, The Nobel Prizes 2019, World Scientific Publishing Company, 2022.

[63] P. Bruce, Rechargable lithium batteries, Philos. Trans. R. Soc. London, Ser. A: Mathematical, Physical and Engineering Science 354 (1996) 1577–1594, https://doi.org/10.1098/rsta.1996.0066.

[64] J.F. Cooper, I.Y. Bong, L.G. O' Connell, E. Behrin, B. Rubin, H.J. Wiesner, Lithium requirements for electric vehicles using lithium-Water-Air batteries, in: J.D. Vine (Ed.), Lithium Resources and Requirements by the Year 2000, Geological Survey Professional Paper, United Sates Government Printing Office, Washington, 1976, pp. 9–12.

[65] M. Garreau, Cyclability of the lithium electrode, J. Power Sources 20 (1987) 9–17, https://doi.org/10.1016/0378-7753(87)80085-X.

[66] S. Szpak, C.J. Gabriel, J.R. Driscoll, Catastrophic thermal runaway in lithium batteries, Electrochim. Acta 32 (1987) 239–246, https://doi.org/10.1016/0013-4686(87)85030-2.

[67] V.R. Koch, Status of the secondary lithium electrode, J. Power Sources 6 (1981) 357–370, https://doi.org/10.1016/0378-7753(81)80040-7.

[68] M. Mohri, N. Yanagisawa, Y. Tajima, H. Tanaka, T. Mitate, S. Nakajima, M. Yoshida, Y. Yoshimoto, T. Suzuki, H. Wada, Rechargeable lithium battery based on pyrolytic carbon as a negative electrode, J. Power Sources 26 (1989) 545–551, https://doi.org/10.1016/0378-7753(89)80176-4.

[69] B. Scrosati, Progress in and future development of ambient temperature lithium batteries, J. Power Sources 11 (1984) 129–134, https://doi.org/10.1016/0378-7753(84)80078-6.

[70] J.-M. Tarascon, M. Armand, Issues and challenges facing rechargeable lithium batteries, Nature 414 (2001) 359–367, https://doi.org/10.1038/35104644.

[71] Tiny Fire Half-Way Around the World Burns up B.C. Firm's High-Tech Dream, Edmonton Journal, 1990.

[72] K. Brandt, Historical development of secondary lithium batteries, Solid State Ion 69 (1994) 173–183, https://doi.org/10.1016/0167-2738(94)90408-1.

[73] E. Jarratt, New lessons from the epic story of Moli Energy, the Canadian pioneer of rechargeable lithium battery technology, Electric Autonomy (2020). https://electricautonomy.ca/2020/09/18/moli-energy-lithium-battery-technology/. (Accessed 12 March 2024).

[74] A. Senyshyn, M.J. Mühlbauer, O. Dolotko, M. Hofmann, H. Ehrenberg, Homogeneity of lithium distribution in cylinder-type Li-ion batteries, Sci. Rep. 5 (2015) 18380, https://doi.org/10.1038/srep18380.

[75] 日経ビジネス (Nikkei Business) Issues 663-667, 日経BP社, Tokyo (1992).

[76] P. Arora, Z, John, Zhang, Battery Separators, Chem Rev 104 (2004) 4419–4462, https://doi.org/10.1021/cr020738u.

[77] L. Lipp, W. An, Report on the electrolytic Industries for the Year 2003, J. Electrochem. Soc. 152 (2005) K1, https://doi.org/10.1149/1.2121738.

[78] M.V. Reddy, A. Mauger, C.M. Julien, A. Paolella, K. Zaghib, Brief history of early lithium-battery development, Materials 13 (2020) 1884, https://doi.org/10.3390/ma13081884.

[79] M.D. Farrington, Safety of lithium batteries in transportation, J. Power Sources 96 (2001) 260–265, https://doi.org/10.1016/S0378-7753(01)00565-1.

[80] K. Kitoh, H. Nemoto, 100 Wh Large size Li-ion batteries and safety tests, J. Power Sources 81–82 (1999) 887–890, https://doi.org/10.1016/S0378-7753(99)00125-1.

[81] Y. Nishi, The development of lithium ion secondary batteries, Chem. Rec. 1 (2001) 406–413.

[82] Loris Nick, Examining the, Department of Energy's Loan Portfolio, 2016.

[83] Global EV Outlook 2020: Entering the Decade of Electric Drive?, IEA Report), 2020. https://iea.blob.core.windows.net/assets/af46e012-18c2-44d6-becd-bad21fa844fd/Global_EV_Outlook_2020.pdf. (Accessed 3 July 2024).

[84] L. Trahey, F.R. Brushett, N.P. Balsara, G. Ceder, L. Cheng, Y.-M. Chiang, N. T. Hahn, B.J. Ingram, S.D. Minteer, J.S. Moore, K.T. Mueller, L.F. Nazar, K. A. Persson, D.J. Siegel, K. Xu, K.R. Zavadil, V. Srinivasan, G.W. Crabtree, Energy storage emerging: a perspective from the Joint center for energy storage research, Proc. Natl. Acad. Sci. USA 117 (2020) 12550–12557, https://doi.org/10.1073/pnas.1821672117.

[85] J. Chiefari, C. Hornung, Mobile hydrogen reformers as a novel approach to decarbonise the transport sector, Curr Opin Chem Eng 34 (2021) 100756, https://doi.org/10.1016/J.COCHE.2021.100756.

[86] S. Okada, 岡田), リチウムイオン電池誕生前後とその未来像, 学術の動向 25 (2020) 2_8–2_15, https://doi.org/10.5363/tits.25.2_8.

[87] W. Cao, J. Zhang, H. Li, Batteries with high theoretical energy densities, Energy Storage Mater. 26 (2020) 46–55, https://doi.org/10.1016/J.ENSM.2019.12.024.

[88] X. Wang, H. Liu, K. Pan, R. Huang, X. Gou, Y. Qiang, Exploring thermal hazard of lithium-ion batteries by bibliometric analysis, J. Energy Storage 67 (2023) 107578, https://doi.org/10.1016/J.EST.2023.107578.

[89] X. Yu, R. Chen, L. Gan, H. Li, L. Chen, Battery safety: from lithium-ion to Solid-state batteries, Engineering 21 (2023) 9–14, https://doi.org/10.1016/J.ENG.2022.06.022.

[90] V. Ruiz, A. Pfrang, A. Kriston, N. Omar, P. Van den Bossche, L. Boon-Brett, A review of international abuse testing standards and regulations for lithium ion batteries in electric and hybrid electric vehicles, Renew. Sustain. Energy Rev. 81 (2018) 1427–1452, https://doi.org/10.1016/J.RSER.2017.05.195.

[91] H. Gabbar, A. Othman, M. Abdussami, Review of battery management systems (BMS) development and industrial standards, Technologies 9 (2021) 28, https://doi.org/10.3390/technologies9020028.

[92] D. Larcher, J.-M. Tarascon, Towards greener and more sustainable batteries for electrical energy storage, Nat. Chem. 7 (2015) 19–29, https://doi.org/10.1038/nchem.2085.

[93] A. Zeng, W. Chen, K.D. Rasmussen, X. Zhu, M. Lundhaug, D.B. Müller, J. Tan, J. K. Keiding, L. Liu, T. Dai, A. Wang, G. Liu, Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages, Nat. Commun. 13 (2022) 1341, https://doi.org/10.1038/s41467-022-29022-z.

[94] M.M. Ciftci, X. Lemaire, Deciphering the impacts of 'green' energy transition on socio-environmental lithium conflicts: Evidence from Argentina and Chile, Extr. Ind. Soc. 16 (2023) 101373, https://doi.org/10.1016/j.exis.2023.101373.

[95] J. Canelas, A. Carvalho, The dark side of the energy transition: Extractivist violence, energy (in)justice and lithium mining in Portugal, Energy Res Soc Sci 100 (2023) 103096, https://doi.org/10.1016/j.erss.2023.103096.

[96] C. Rafele, C. Gallo, G. Mangano, A.C. Cagliano, A. Carlin, Low impact vehicle battery supply chains: assessing the impacts of alternative procurement strategies, Int. J. Electr. Hybrid Veh. (IJEHV) 13 (2021) 127, https://doi.org/10.1504/IJEHV.2021.117848.

[97] C. Rafele, G. Mangano, A.C. Cagliano, A. Carlin, Assessing batteries supply chain networks for low impact vehicles, Int. J. Energy Sect. Manag. 14 (2020) 148–171, https://doi.org/10.1108/IJESM-11-2018-0004.

[98] J.M. Tarascon, D. Guyomard, The Li1+xMn2O4/C rocking-chair system: a review, Electrochim. Acta 38 (1993) 1221–1231, https://doi.org/10.1016/0013-4686(93)80053-3.

[99] A.K. Krüger, M. Reinhart, Theories of valuation - Building Blocks for conceptualizing valuation between practice and structure, Hist. Soc. Res. 42 (2017) 263–285.

[100] D.S. Mackay, What does Mr. Dewey mean by an "indeterminate situation", J. Philos. 39 (1942) 141, https://doi.org/10.2307/2018415.

[101] D. Wilson, S. Dan, Outline of relevance theory, HERMES-Journal of Language and Communication in Business 5 (1990) 35–56.

[102] J. Liu, J. Li, J. Wang, In-depth analysis on thermal hazards related research trends about lithium-ion batteries: a bibliometric study, J. Energy Storage 35 (2021) 102253, https://doi.org/10.1016/j.est.2021.102253.

[103] K. Li, Q. Su, X. Ma, H. Zhang, Research on lithium technology safety issues: a bibliometric analysis, Sustainability 15 (2023) 4128, https://doi.org/10.3390/su15054128.

[104] S. Chen, J. Xiong, Y. Qiu, Y. Zhao, S. Chen, A bibliometric analysis of lithium-ion batteries in electric vehicles, J. Energy Storage 63 (2023) 107109, https://doi.org/10.1016/j.est.2023.107109.

[105] O. Dedehayir, S.J. Mäkinen, Determining reverse salient types and evolutionary dynamics of technology systems with performance disparities, Technol. Anal. Strateg. Manag. 23 (2011) 1095–1114, https://doi.org/10.1080/09537325.2011.621308.

[106] H.-C. Lo, C.-Y. Wu, M.-C. Hu, Acting as an innovation niche seeder:how can the reverse salient of southeast Asian economies be overcome? J. Evol. Econ. 30 (2020) 1195–1217, https://doi.org/10.1007/s00191-020-00685-5.

[107] R. Boutellier, K. Loffler, Bottleneck technologies: Applying the constraints approach to technology management Evidence from case studies, in: 2006 Technology Management for the Global Future - PICMET 2006 Conference, IEEE, 2006, pp. 38–45, https://doi.org/10.1109/PICMET.2006.296551.

[108] Y. Liu, I. Alnafrah, Y. Zhou, A systemic efficiency measurement of resource management and sustainable practices: a network bias-corrected DEA assessment of OECD countries, Resour. Pol. 90 (2024) 104771, https://doi.org/10.1016/j.resourpol.2024.104771.