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Hype Cycle Assessment Of Emerging Technologies For Battery Production

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Abstract

The demand for battery-powered electric vehicles is growing rapidly as more and more OEMs are shifting their strategy towards an all-electric vehicle fleet. The lithium-ion battery cell is considered as the core component in terms of performance, range and price of electric vehicles. Since the development of the functional principle of the lithium-ion battery, both the product and the associated production technology have evolved significantly. OEMs, start-ups, equipment suppliers and other players in the automotive industry are investing heavily in research and development of various technologies to improve both the battery as a product and its production. An essential aspect is to enable sustainable battery production. While breakthroughs in battery technology are regularly announced, the actual merits of the technologies and the potential remain uncertain until commercial deployment. The aim of this paper is to systematically identify upcoming breakthroughs and announced innovations to provide an overview of promising battery technologies that companies should focus on to enable the planning of resilient and sustainable production systems. Hence, a hype cycle assessment following Gartner was adopted as the underlying approach to evaluate battery technologies for deployment in electromobility and mass production. First, various technologies, innovations, research activities and announcements in the field of battery technologies were screened, recorded and classified in order to obtain an overview of the current state of developments on both product and production levels. This includes an overview of innovations in battery design and configuration as well as process technologies and production systems. Subsequently, these technologies are evaluated according to predefined evaluation criteria in order to enable a systematic classification of the individual technologies in the hype cycle. The result is a consolidated overview of emerging battery technologies for sustainable battery production and a display for further recommendations for relevant companies and stakeholders.

Keywords

Hype Cycle; Technology Assessment; Lithium-Ion Battery; Battery Production

1. Introduction

In order to become independent of fossil fuels and minimize greenhouse gas emissions, a change in mobility is essential. A major step in this sector is electrification, thus increasing the importance of batteries as one of the key drivers. [1,2] Because of their excellent properties for use as a rechargeable energy storage system, lithium-ion batteries (LIBs) have established themselves in various applications from consumer electronics up to stationary storage systems. Especially in the automotive industry, batteries gained significant importance as a key technology for electric vehicles (EV). Due to the current pace of automotive

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electrification, the global demand for lithium-ion batteries is projected to surpass over 3,970 GWh in 2030. [3]

Lithium-ion batteries have become the focus of research in recent years. New battery concepts and material combinations are being researched and developed to meet current demands and to drive further developments. Also, the production of battery cells requires improvement through innovation. Recent studies shown that the production of 1 Wh of storage capacity requires a cumulative energy demand of 328 Wh [4]. Since the battery cell production is very energy and time consuming, resulting in high manufacturing costs, innovative approaches towards a greener cell production must be advanced. [5,6].

Breakthroughs for product and process innovations in the field of battery technology are regularly presented in scientific journals and announced by companies. However, the progress and significance of these research activities and developments of various innovations cannot always be concluded from the quantity of announcements. Therefore, new technologies and innovations need to be systematically identified and assessed from the multitude of announcements. Hence, an approach for the evaluation of technologies needs to be explored to provide an aggregate and generalized overview of emerging battery technologies and to derive a long-term strategy regarding future activities and developments for various stakeholders. In this paper, a variety of product and process innovations in battery technology were identified, analysed according to the hype cycle and classified in a priority matrix. Subsequently, an aggregated overview of emerging battery technologies was created to enable a long-term orientation.

2. Fundamentals on lithium-ion technology

Current advancements and technological trends are based on the ongoing market drivers and requirements for the lithium-ion battery. Some of the key market drivers and requirements are energy density, power density, safety, life cycle behaviour, product quality, life-time, product safety, cost and expenditure, and sustainability. However, it is not yet possible to maximize all these properties with a single cell chemistry or design. Therefore, during system development, the appropriate cells and their properties must be carefully selected and designed depending on the application. [7,8]

The energy density is decisive for EVs, as it determines the range to a large extent. [9] A high power density enables fast charging capabilities of the battery or fast acceleration of an EV. [10] The lifetime is determined by the electrochemical processes within a cell that lead to the decrease of cell capacity and performance. Regardless of the battery, a distinction is made between two forms: calendrical and cyclical life. [11] For EVs, battery cells are generally required to have a service life of more than 10 years [7]. Safety-critical situations can arise when external influences such as high temperatures or mechanical impacts occur [7]. In particular, the cost factor is constantly improved to reduce the costs of battery systems, as it is responsible for up to 33 % of the total cost of an EV. [12] Lithium-ion batteries have emerged as a key technology and currently strongly dominate the market as they meet and satisfy most requirements and market drivers for EVs to a high degree.

2.1 Basic structure and cell formats of LIBs

A LIB in its basic form is composed of the following main components: two electrodes (anode and cathode), a separator and the liquid electrolyte. The anode typically consists of a copper foil coated with graphite. The cathode typically is composed of aluminium foil coated with a lithium-containing compound as an active material. The separator is a porous membrane, that electrically isolates the two electrodes, yet allows ions to pass through. The electrolyte consists of an ionic conducting salt and serves as a transport medium for the ions between the two electrodes. [13] The term lithium-ion battery covers various chemistries and material combinations [14]. While carbon composites such as graphite are usually used as the active material for the anode, different cathode lithium-containing materials can be seen. [15,16]

There are currently three battery cell formats used for mass application in EVs: Pouch, cylindrical and prismatic cells [17]. The various battery cell formats use the same general structure as described previously. They mainly differ in the design and manufacture of the inner cell composite and thus in the outer shape. Depending on the application, different battery cell formats can be beneficial. In general, the production and application experience are most profound with cylindrical cells, as they have been commercially used in many consumer applications since 1991. Higher energy and packing densities can be achieved with pouch cells. However, they are more susceptible to deformation as they only consist of a thin pouch foil as a cell casing. The prismatic cell combines properties of both cell types and offers high packing densities on module level with higher bending stiffness. [18] For use in EVs, the single battery cells are assembled to a module. The module consists of the cell stack, a wiring harness, the module housing and the bracing. Afterwards, the modules are integrated into a battery system, that typically consists of several modules, the electrical and thermal management system as well as the casing and external interfaces. [7,19]

2.2 Production process for LIB manufacturing

The production of battery cells can be divided into three main segments starting with the electrode manufacturing, followed by cell assembly and lastly cell finishing. Figure 1 shows a schematic overview of the production processes of the three battery cell formats: pouch, cylindric and prismatic cells.

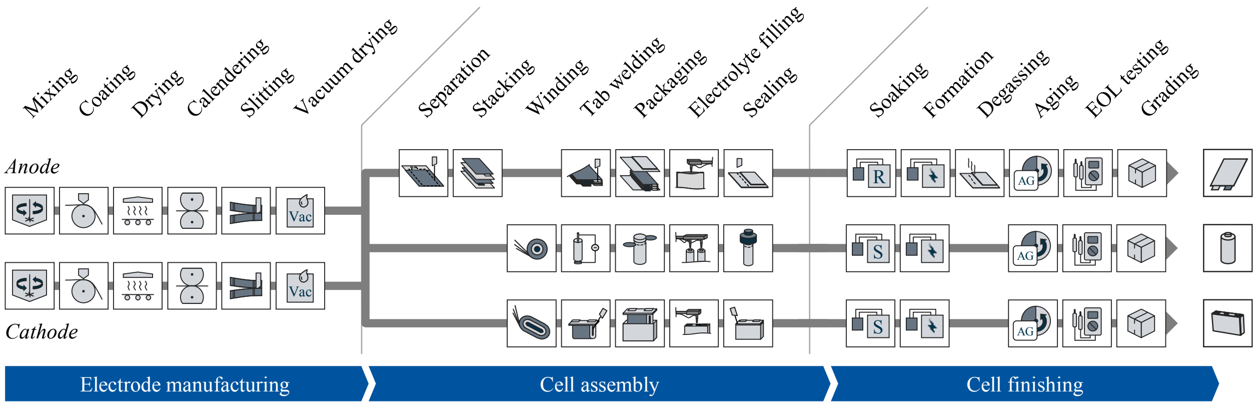

Figure 1: Overview of the general process chains for manufacturing of different lithium-ion battery cell formats

In electrode manufacturing, material-specific anodes and cathodes are produced using two separate lines. First, the active materials are mixed into a slurry. Afterwards the slurry is coated onto a thin metal foil and dried. After two roll-to-roll processes, calendaring and slitting, the finished electrode is vacuum dried and transported to the next production section. In cell assembly, the used process technology and sequence are strongly influenced by the cell format. First, alternating layers of anode, separator and cathode are assembled to form the inner electrode-separator composite (jelly-roll or stack). After the packaging and electrolyte filling, the cell housing is sealed und the cell is fully assembled. In cell finishing, the battery cell is charged for the first time to establish the final electrochemical properties of the cell. Starting with soaking of the electrolyte, the formation is done by controlled charging and discharging cycles. During this process, gases can occur which must be evacuated. After a monitored storage (aging), the end-of-line (EOL) testing is conducted and the cells get graded according to their quality. The process flow in cell finishing is almost identical for the cell formats, but the equipment may differ in its technical realization. [19,20]

2.3 Innovation and emerging battery technologies

Innovations are an essential factor for long-term success and capability to compete globally. Innovations can be described as "the development and implementation of an innovative idea that generates tangible added value" [21]. In this context, the pursuit of technological progress and the object of innovation can have very different characteristics, ranging from products and production processes to services and organizations. Next to focused advancement of certain technologies, entire industries can be influenced by overall market trends such as ‘Internet of Things’ or the discovery of new material applications. [21]

In this paper, the focus is on product and process innovations in battery technology. When referring to advancements, innovations and emerging technologies in this paper, the established state of the art of LIB and the previously described prevalent process chain and technologies for battery cell production form the basis.

Product innovations generally describe new or improved products by technically enhancing an existing product, adding a new product feature to the existing portfolio or creating a completely novel product line. Typically, product innovations follow an external perspective by focusing on the customer or the application of the product, whereas process innovations often pursue an internal perspective by focusing on the processes and operations. Process innovations result from novel combinations of manufacturing techniques and aim at more efficient, reliable and economical as well as high-quality and green production by implementing certain improvements (e.g. tools, controls, sensors). [21,22,23] Product and process innovations are often linked, as new processes are needed to produce innovative products or new product opportunities are created through innovative processes. The introduction of different types of innovations can lead to different competitive advantages. [21,22]

Breakthroughs in a variety of different battery technologies are announced regularly. Numerous battery chemistries and designs have been researched and demonstrated in laboratory or prototype applications. Major advances in cell chemistry and material composition for battery applications typically aim to increase key properties such as energy and power density. But various innovations and technologies are also emerging in the context of production. There are many critical process steps along the entire process chain that are decisive for the quality of the battery cell. Also, since the production of battery cells is time and energy consuming, energy-efficient and accelerated processes are essential, among other aspects, to reduce battery costs and increase productivity.

3. Method and approach

The field of battery research has been explored intensively for years, and various technologies are advancing rapidly. In this dynamic environment, a frequent overview of upcoming technologies is essential for industry and research. Literature is filled with various battery roadmaps, reviews and assessments of current and future battery manufacturing [24,25,26,27]. Yet, these assessments are focused on single approaches regarding a certain technology or its implementation (e.g. dry coating) or they compare a few technologies regarding one specific topic (e.g. battery materials). There was no paper found that provides a holistic overview for strategic development of the multitude of battery technologies in the future.

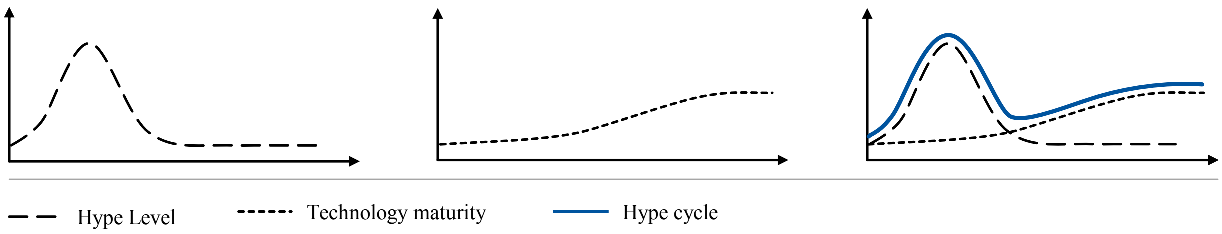

Figure 2: Hype cycle by combining hype level and technology maturity [28]

In 1995 Gartner Inc. introduced the Gartner Hype Cycle which is intended to be a graphical representation of the hype (expectation) of a technology over time. As similar patterns of hype and disillusionment can be applied to various concepts and technologies, an assessment approach based on Gartner's Hype Cycle was used in this paper to evaluate product and process battery technologies. The hype cycle is an accumulation of two effects: The hype level and the technology maturity (Figure 2). The graph reflects the nature of enthusiasm as the technology develops. Gartner has normalized the vertical scale as the expectations for each technology may vary based on its importance to industry and society. Thus, all individual hype curves fit into one hype cycle. The time is plotted on the horizontal axis and divided into five stages. Every technology will proceed through each stage, but each at its own pace. Some technologies might be in a particular phase for a short time, while others might persist for a longer period to reach mainstream adoption. [28,29]

3.1 Criteria for the hype cycle assessment

As Gartner's initial analysis of the hype cycle is mainly focused on information technologies, the assessment categories and their criteria had to be modified in order to adapt them for battery products and processes. The goal of the assessment is to identify the current hype of a technology and to evaluate the technological maturity, the time to market, and the overall potential. Therefore, the hype cycle assessment was conducted based on these four categories.

Hype level is based on the phases of the Gartner Hype Cycle and comprises five levels. As the interest in an innovation grows, so do the expectations until the pinnacle of expectation is reached. [30] The respective hype level of a technology is determined based on a consensus assessment of the maturity level and the frequency of reports and announcements.

Readiness level describes the maturity of a technology, a design or a process. The maturity was classified according to the readiness levels. The technology readiness level (TRL) was introduced by NASA to support the "tracking [of] technologies in development and their transition into production" [31]. The manufacturing readiness level (MRL) refers to development activities "when a (manufacturing) technology or process is matured and transitioned to a system" [31]. TRL and MRL share a similar numbering system by using a common metric and vocabulary for assessing readiness and technology risk described in detail in [31].

Potential describes the expected benefit of a technology. Each type of technology was evaluated and measured against defined reference points (e.g. product quality, cost reduction, energy consumption). In each case, the potential refers to a fully mature technology and not to the current development status. For the identified technologies, the current state of the art for LIB and cell production was used as a reference.

Time-to-market describes the duration until the technology will enter the market and will be commercially available. Since maturity is not related to market availability, it is also possible that a technology is on the market and at the same time is not yet fully mature. The final assessment regarding time to market were made based on various announcements, which have been reviewed and affirmed regarding their plausibility.

3.2 Approach for technology research and scouting

The scouting and evaluation of emerging innovations in the field of battery technology was conducted in four steps: initial scouting, information gathering, technology evaluation and final aggregation. This approach enabled to systematically translate the wide range of innovations, announcements and activities into a final selection of technologies. The goal was to identify various product and process technologies in the battery industry.

The technology research was conducted based on a scouting in various sources, including scientific journals and databases (IEEE Xplore, Web of Science, MDPI, Elsevier, etc.), as well as public presentations and proceedings of conferences (Future Battery Forum, The Battery Show, AABC, etc.). Additionally, news sites (battery-news.de, electrive.net, etc.) were reviewed, along with expert panels (e.g. the Battery Brunch), battery roadmaps (e.g. VDMA, Fraunhofer), as well as press articles and events like the Tesla Battery Day and Volkswagen Power Day. Patents were searched using search terms such as "battery," "lithium-ion battery," "battery cell production," and "battery production". This comprehensive approach ensured that emerging battery technologies were identified, enabling a systematic selection of promising technologies across a wide range of sources. The search was conducted between October 2021 and December 2022. An iterative screening process was used to determine whether the technology was state of the art or a novel approach.

After the preliminary scouting a total of 65 technologies have been listed. An initial assessment of the technology's utility was also conducted. Since some development activities are aimed at a similar or the same technology, a few innovations have been combined in this case (e.g. optimized NMC compositions such as NMC-955 or NMx), leaving a total of 54 technologies. During the technology evaluation, further research was conducted to obtain sufficient data for a valid assessment. Expert interviews were added to challenge or expand upon the available information for certain technologies, if needed. The technology research was concluded with a set of 39 technologies for both product and process innovation.

4. Results

The following section presents the results of the hype cycle assessment for battery technologies and derives a priority matrix based on potential benefits.

4.1 Hype cycle for emerging battery technologies

The battery hype cycle for emerging battery technologies is shown in Figure 3. The technologies are divided into product and process innovations. Due to the tremendous efforts in various research areas, the overview is a snapshot in time, in which certain innovations may progress faster than others.

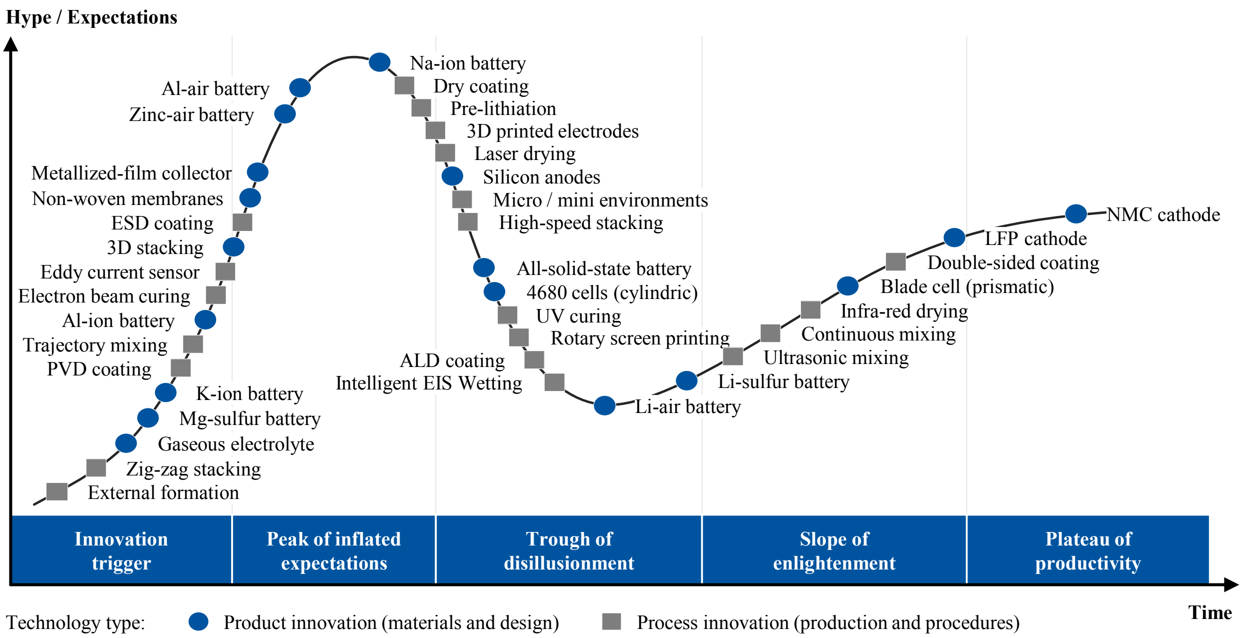

Figure 3: Battery hype cycle for emerging battery product and production process technologies (as of 2023)

Product innovation: A total of 17 technologies at battery product level have been considered. A majority of the emerging product technologies focus on innovations in material pairing and combinations for the battery cell active material. Lithium-based materials such as LFP but also lithium-sulphur or lithium-air batteries are beyond the hype and advancing in their development. Currently, sodium-ion, aluminium-air, zinc-air and aluminium-ion batteries are experiencing a major hype. However, high expectations are also being placed on novel material combinations such as potassium-ion or magnesium-sulphur batteries. Other product innovations focus on novel product designs such as large-format cells, e.g. prismatic blade cells or cylindric 4680 cells. On the other hand, individual key components of the battery cell are being further advanced, e.g. non-woven membranes or metallized plastic foil current conductors for increased intrinsic safety of the battery cell.

Process innovation: In total, 22 technologies have been considered in the context of production. Noticeably, many of the process innovations focus on advancing single aspects or steps of the current LIB manufacturing processes rather than overall production. One focus area is the reduction of energy costs, e.g. through improved drying technologies such as infra-red drying, UV curing, laser drying or controlling the process atmosphere in energy-efficient mini-environments. Besides, various coating processes are investigated which would render the drying process obsolete, e.g. ALD coating, ESD coating or 3D printed electrodes. Dry coating is receiving a particularly large amount of attention. In addition, some other process steps are optimized by innovations regarding their process quality and efficiency, such as continuous mixing, high-speed stacking or intelligent EIS wetting. Others focus on improving product quality, for example eddy current sensors for inline quality inspection of the active material slurry or pre-lithiation for increased cell capacity.

The selected technologies show the broad spectrum of current research activities. In this context, it is important to emphasize that the battery hype cycle does not claim to be exhaustive, but rather provides a representative overview of current developments and innovations and must be updated and aligned on a regular basis for further evaluation.

4.2 Priority matrix for strategic technology selection

The priority matrix contains additional information about the potential or benefits of an innovation or technology. It is a tool for presenting innovation opportunities and covers all the technologies presented in the hype cycle. Unlike the hype cycle, the priority matrix does not focus on the hype or attention a technology gets, but on its prospective benefits. However, its value is in providing decision support on which technologies a company should focus on or invest in. Therefore, the rating of the potential is sorted into four categories: transformative, high, moderate, and low. This is then combined with the expected time to market. In Figure 4, the derived priority matrix from the battery hype cycle is shown.

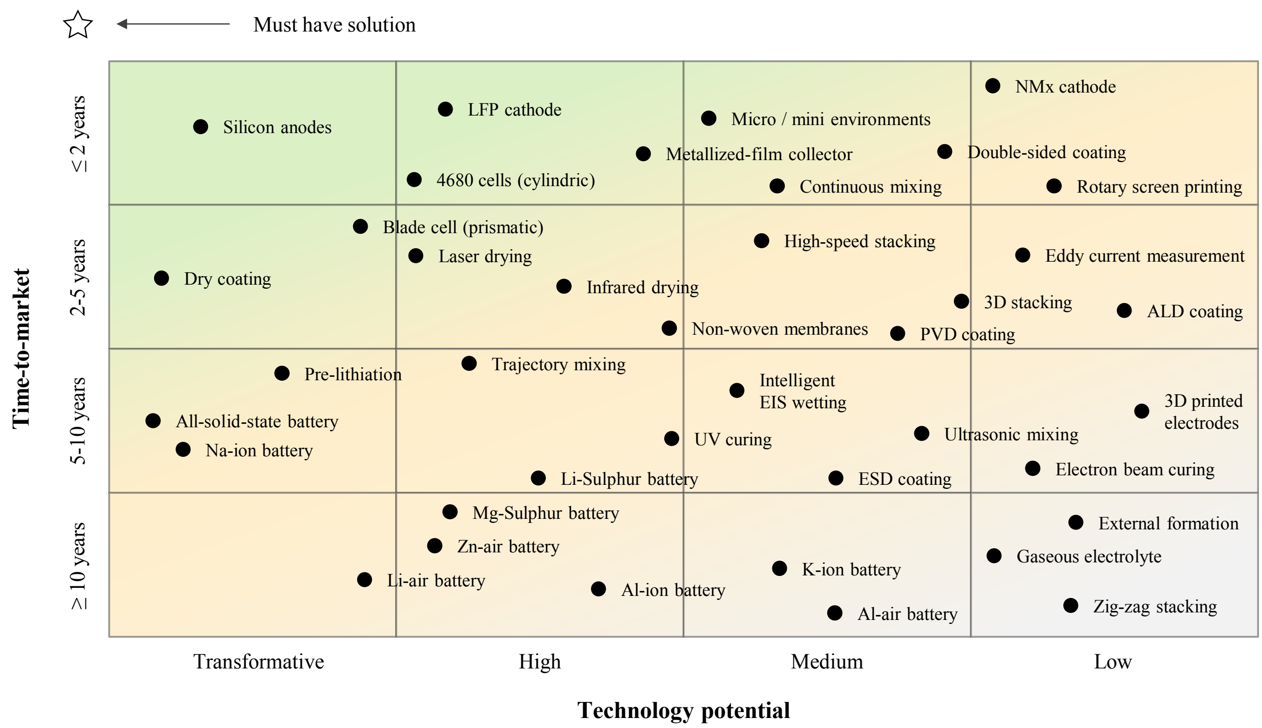

Figure 4: Priority matrix for emerging battery technologies

In the technology assessment, seven technologies were identified that are expected to fundamentally transform the current market for automotive battery technologies. On the product level, transformative innovations include silicon anodes, as they will increasingly displace graphite in particular as an active material for anodes from the market in the upcoming years. Apart from this, current trends already show that large-format cells are more and more prominent and especially blade cells (prismatic) are prone to enable the cell-to-pack approach. Furthermore, novel material compositions are becoming increasingly important, with sodium-ion (more abundant and less expensive) and all-solid-state (high energy density and more stable) batteries. However, their full market maturity is not expected for another 5 to 10 years. In the manufacturing context, dry coating and pre-lithiation are seen as transformative, as their market introduction may enable new processes and procedures for all battery material technologies, which will lead to major changes in the dynamics of battery production. [32] Other innovations expected to reach full market maturity, particularly in the next 2 years, include large-format 4680 cells (cylindrical), the widespread introduction of LFP cathodes to take NMC shares, and the introduction of mini-environments, continuous mixing and simultaneous double-sided coating. As for 4680 cells first announcements about mass production were made and terminated for a time within the next two years, also emphasizing silicon anodes as they are both a transformative and an upcoming technology [34,33].

The priority matrix shows that technologies located in the upper left corner are particularly relevant and directly seeking involvement in these technologies should be explored. The technologies which can be found in the lower right corner are recommended to be observed or invested in with caution as these technologies show a relatively low benefit on the battery industry and won't reach the plateau of productivity within the next 10 years.

4.3 Discussion

In comparison to other reviews dealing with the assessment of battery technologies, this paper addresses a holistic overview of innovations in the context of battery application in EVs and its manufacturing in mass production. This hype cycle can provide an initial basic strategic orientation for a broad number of stakeholders. For specific industries or companies, however, the hype cycle assessment should be focused to address specific areas. Pantoja et al. [26] for example compare different materials for alternative battery technologies and conclude with two material hype cycles for promising anode and cathode materials. The same approach and level of detail might be useful, for example, for a focus in the area of mechanical and plant engineering (e.g. application of laser technologies in battery production), and must therefore be specified depending on the industry and use-case of the hype cycle.

The sentiment of publications can generally not be measured but it plays a significant role in the positioning of a technology. Especially publication with a negative sentiment can cause a decrease in the hype and a tendency for the technology to enter the trough of disillusionment. Thus, the publication number is no longer sufficient to give an accurate picture. Since the assessment is based on public literature and announcements, a dark figure of missing information has to be considered. This include unrestricted and global access to intellectual property and research results, as well as the industrial research and development activities of individual companies that keep their results under lock and key until final application.

5. Conclusion

In this paper, emerging technologies for battery production have been evaluated using a hype cycle assessment regarding the expectations and maturity of various technologies. The assessment provides an overview of where a technology is in its development lifecycle and helps identifying promising technologies. Yet, a hype cycle is only representing a snapshot at a particular point in time. The hype cycle derived in this paper includes a total of 39 product and process technologies. The priority matrix shows, the classification of technologies according to their respective benefits and time-to-market. Nonetheless, the assessment shows to be useful for identifying potential opportunities and challenges related to the adoption of new technologies in the battery manufacturing industry and helps companies make informed decisions about which technologies to invest in and how to position themselves in the market. Further research is necessary to identify and setup a systematic approach on how to face individual technical challenges for the strategically selected emerging technologies that must be overcome and how they can be commercialized.

Acknowledgements

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Appendix

Table 1 shows the assessment of the selected emerging battery technologies based on the defined assessment criteria. Please note that this overview indicates the status as of mid-2023. New findings due to vast market dynamics and current technology developments require a regular review and update of this list.

Table 1: Assessment of emerging battery technologies

#	Battery technology	Hype cycle	Readiness	Potential	Time-to-m.
1	4680 cells (cylindric)	Trough of disillusion	TRL 7-8	High	≤ 2 years
2	3D printed electrodes	Trough of disillusion	TRL 5-6	Low	5-10 years
3	3D stacking	Innovation trigger	TRL 3-4	Medium	2-5 years
4	All-solid-state batteries	Trough of disillusion	TRL 5-6	Transform.	5-10 years
5	ALD coating	Trough of disillusion	TRL 3-4	Low	2-5 years
6	Al-air battery	Peak of expectations	TRL 3-4	Medium	≥ 10 years
7	Al-ion battery	Innovation trigger	TRL 5-6	High	≥ 10 years
8	Blade cell (prismatic)	Slope of enlightenment	TRL 9	Transform.	2-5 years
9	Continuous mixing	Slope of enlightenment	TRL 7-8	Medium	≤ 2 years
10	Double-sided coating (simult.)	Slope of enlightenment	TRL 9	Medium	≤ 2 years
11	Dry coating	Peak of expectations	TRL 5-6	Transform.	2-5 years
12	Eddy current measurement	Innovation trigger	TRL 3-4	Low	2-5 years
13	Electron beam curing	Innovation trigger	TRL 5-6	Low	5-10 years
14	ESD coating	Peak of expectations	TRL 3-4	Medium	5-10 years
15	External formation	Innovation trigger	TRL 1-2	Low	≥ 10 years
16	Gaseous electrolyte	Innovation trigger	TRL 3-4	Low	≥ 10 years
17	High-speed stacking	Trough of disillusion	TRL 3-4	Medium	2-5 years
18	Infrared drying	Slope of enlightenment	TRL 9	High	2-5 years
19	Intelligent EIS wetting	Trough of disillusion	TRL 3-4	Medium	5-10 years
20	K-ion battery	Innovation trigger	TRL 3-4	Medium	≥ 10 years
21	Laser drying	Peak of expectations	TRL 3-4	High	2-5 years
22	LFP cathode (Li-ion)	Slope of enlightenment	TRL 9	High	≤ 2 years
23	Li-air battery	Trough of disillusion	TRL 3-4	Transform.	≥ 10 years
24	Li-sulphur battery	Trough of disillusion	TRL 3-4	High	5-10 years
25	Metallized-film collector	Peak of expectations	TRL 7-8	High	≤ 2 years
26	Mg-sulphur battery	Innovation trigger	TRL 3-4	High	≥ 10 years
27	Mini-environments	Trough of disillusion	TRL 7-8	Medium	≤ 2 years
28	Na-ion battery	Peak of expectations	TRL 7-8	Transform.	5-10 years
29	NMC cathode (Li-ion)	Plateau of productivity	TRL 9	Low	≤ 2 years
30	Non-woven membranes	Peak of expectations	TRL 5-6	High	2-5 years
31	Pre-lithiation	Peak of expectations	TRL 7-8	Transform.	5-10 years
32	PVD coating	Innovation trigger	TRL 3-4	Medium	2-5 years
33	Rotary screen printing	Trough of disillusion	TRL 9	Low	≤ 2 years
34	Silicon anodes	Trough of disillusion	TRL 9	Transform.	≤ 2 years
35	Trajectory mixing	Innovation trigger	TRL 5-6	High	5-10 years
36	Ultrasonic mixing	Slope of enlightenment	TRL 3-4	Medium	5-10 years

37	UV curing	Trough of disillusion	TRL 7-8	High	5-10 years
38	Zig-zag stacking	Innovation trigger	TRL 3-4	Low	≥ 10 years
39	Zn-air battery	Peak of expectations	TRL 5-6	High	≥ 10 years

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