Future in Battery Production: An Extensive Benchmarking of Novel Production Technologies as Guidance for Decision Making in Engineering

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***Abstract*—Due to the rising interest in electric vehicles, the demand for more efficient battery cells is increasing rapidly. To support this trend, battery cells must become much cheaper and “greener.” Energy consumption during production is a major driver of cost and CO_2 emissions. The drying production step is one of the major energy consumers and cost drivers. The technological approach of “dry coating” allows the energy-intensive drying step to be eliminated for significant energy and cost savings. However, there are numerous emerging dry coating technologies that differ significantly in physics, chemistry, and readiness levels. Moreover, typical methodological procedures for technology selection remain less applicable to the early stages of technological development. Both issues raise the questions, “What is the most promising dry coating technology?” and “How do we identify it?” To answer these questions, a comprehensive, systematic technology benchmark was conducted. Following a four-step analytical approach, based on the nominal group technique, qualitative content analysis, and multicriteria decision analysis, different dry coating technologies were identified, analyzed, and cross-compared. This was performed qualitatively and quantitatively. We also forecast which factor will impact the application of the most promising technologies for CO_2 emission rate reductions and cost savings in 2030. In summary, four different technologies were identified with a high chance of technological breakthrough within the next 3–5 years. By applying these technologies, 4.76 million tons of CO_2 could be saved per year by 2030.**

***Index Terms*—Battery cell production, cost reduction, dry coating, energy consumption, technology benchmark.**

I. INTRODUCTION

THE international demand for electric vehicles is rising rapidly, and the demand for battery cells with it, especially for lithium-ion battery cells [1]. In 2015, the worldwide demand for lithium-ion battery cells was approximately 70 GWh/a [2], whereas the WEF predicts a worldwide demand in 2030 of 2623 GWh/a [3]. Tesla’s CEO Elon Musk even predicts a future demand of 10 000 GWh/a [4] without naming an exact year. Although this overall development might be beneficial in terms of ecological sustainability, the production of battery cells requires a high amount of energy. Meta-studies state a quite large range of energy consumption for battery cell production of 100–180 kWh per kWh of produced battery capacity [5], not taking into account the energy required to mine and refine the constituent materials, such as lithium and cobalt. This is equal to an approximated CO_2 equivalent between 70 and 110 kg CO_2-eq per kWh of produced battery capacity [5]. Based on these numbers in 2030 for a predicted demand of 2623 GWh/a lithium-ion cell capacity [3], 262–472 TWh of energy is needed for worldwide battery production. This is an annual CO_2 equivalent of 184–289 million tons of CO_2, which is equal to the annual CO_2 turnover of approximately 150 000–240 000 km^2 of beech forest [6]. On average, this is the entire forest area of Finland, i.e., 22 2180 km^2 [7]. Taking this into account, it is conceivable that battery production will be a major energy consumer and source for CO_2 emissions in the near future.

Many promising technologies have a high potential to reduce energy consumption and thereby significantly reduce the cost of battery cell production. Among these, “dry coating” is one of the most promising technologies [8]. By eliminating the entire drying procedure in the electrode coating, large amounts of energy can be saved [9]. However, dry coating technology has not yet been applied on a large scale in the battery manufacturing industry, as none of the existing technological approaches has sufficient readiness. In addition, difficulties have been reported that technologies at an even earlier stage of development have not been considered in some quantitative data collection and evaluation methods. This difficulty is underpinned by recent work seeking to identify the evaluation criteria for technology selection, particularly in the early stages [10], [11]. Furthermore, not only are there many different approaches to realizing dry coating but the relevant information is widely scattered in the literature and often unpublished, making it difficult to identify the relevant dry coating technology approaches and the most promising approach. Thus, this study will answer the questions, what is the most promising dry coating technology, and how can it be identified?

The remainder of this article is structured as follows. First, in Section II, an overview of the research setting and the theoretical and practical background is provided in the context of innovation and technology management. Here, an overview of the methodological approaches to technology selection, especially for technologies in the early stages of development, is given. In

Manuscript received January 10, 2021; revised May 20, 2021, September 2, 2021, and November 17, 2021; accepted January 16, 2022. This work was supported by the German Federal Ministry of Education and Research (BMBF) under Grant 03XP0256. Review of this manuscript was arranged by Department Editor S. Walsh. *(Corresponding author: Florian Degen.)*

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Digital Object Identifier 10.1109/TEM.2022.3144882

Section III, the technical case of this study is introduced, namely battery cell manufacturing and the use of dry coating technology for electrode manufacturing. In Section IV, the methodological approach is described, and in Section V, the results are presented and discussed. In Section VI, the scientific contributions of the study as well as implications, limitations, and an outlook are provided.

II. RESEARCH SETTING, THEORETICAL, AND PRACTICAL BACKGROUND

A. Battery Technology in the Context of Innovation and Technology Management

Battery and energy storage technologies are currently attracting great interest in a variety of scientific research fields. The high innovation potential that goes hand in hand with the implementation of efficient and demand-oriented storage technology for electrical energy has a long history [12]–[15]. An important milestone that also enabled the importance of battery technologies for product innovations, especially for mobile consumer applications, was the milestone commercialization of the lithium-ion battery by Sony Corp., Tokyo, Japan, in 1991 [16]. These key historical technological developments associated with the market launch are still the foundation of contemporary accomplishments through countless optimization approaches [17].

Currently, the latest lithium-ion battery cell technology is also the subject of scientific work in the field of innovation and technology management in relation to both battery cell production and their applications as energy storage devices. Its role as an enabler of technology in the context of sustainable transitions has been addressed in numerous studies. On the one hand, it plays a key role in the development of an electrified mobility sector [18]–[22]; on the other hand, it is crucial to the development of smart energy grids and optimized integration of renewable energies [23], [24]. Further lines of research treat battery technologies as an object of investigation on a meta-level, independent of a specific application. These studies usually investigate topics of industry/technology-dependent innovation strategies [25]–[27] and knowledge diffusion [28]–[33], as well as the specifics of technological change [34]–[36] and influencing variables of innovation and energy policies [37], [38]. In addition to studies that focus on scientific knowledge in empirical investigations of various theoretical and application-oriented problems, there is also research that focuses on the development of methods using the example of energy storage technologies. Examples are studies of developments in patent analytics [39]–[41], roadmapping [42], semantic analyses [43], and portfolio techniques, [44]. This indicates both a high relevance of the subject area and suitability for generalizability.

B. Technology Selection on the Case of Battery Cell Production

One important task of technology management is to provide the information leadership needs to make informed decisions for or against operational activity on a product- or process-related technology. Past studies of lithium-ion battery cell manufacturing have tended to be empirical, covering a broad field comprising materials processing [45], life-cycle analysis [46]–[48], recycling routes [49]–[51], process simulations [52], [53], and cost models [54]–[56]. However, structured evaluations of the technological deployment of manufacturing technologies remain scarce despite the existence of technological alternatives and a suitable methodology for an objective comparison for battery cell manufacturing. To the best of our knowledge, the only study applying a technology selection methodology to energy storage technologies is the work of Daim *et al.* [57], which investigated the role of energy storage in stationary applications, but not the industrial manufacturing process.

C. Technology Selection in the Context of Emerging Technologies—Methods, Frameworks, and Indices

Fundamental work on the development of technology strategies involves the tasks of technology acquisition, technology management, and technology exploitation [58]. Technology acquisition comprises several possible approaches, such as inhouse research and development, joint ventures, contract research, and licensing. The choice of approach depends on the life cycle position as well as the urgency. The mode of joint R&D activities allows for very early technology acquisition, but at the cost of high commitment. Before initiating a technology acquisition process, however, further steps are needed, such as technology identification and technology selection. These first cover the creation of an overview of possible technological alternatives (technology identification), as well as the decision on the selection of technologies to be integrated into one's operational process (technology selection) [59].

An overview of the established methods of technology selection is given by Hamzeh *et al.* [60]. The methods discussed are primarily quantitative, which inevitably requires the availability of appropriate data. However, previous studies have reported difficulties in evaluating emerging technologies [61]–[63]. This often results from an insufficient database, which complicates the applicability of the quantitative methodology. Shen *et al.* investigated technology selection in the case of emerging technologies based on a hybrid methodological approach that also includes a structured, patent-based section [64]–[66]. The problem with this methodological approach is that technologies at an even earlier prepatent stage (or at their patents' prepublished stages) are not considered by patent analysis and thus require a different data acquisition method. The difficulty is underpinned by recent work concerned with the identification of evaluation criteria for technology selection at early stages [10], [11].

One evaluation parameter for technology selection that should be emphasized is the technological readiness level (TRL) because of its relevance in determining the specific technology attractiveness [67], [68]. The concept of technological readiness was first introduced by the National Aeronautics and Space Administration (NASA) in the 1960s and later formalized in the form of technology readiness levels (TRLs) [69]. The goal was to provide a systematic measurement system for assessing the

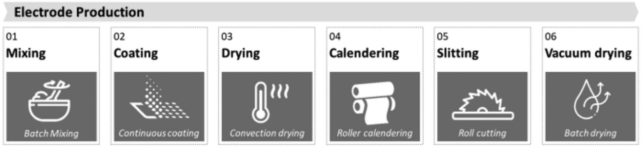


Fig. 1. Production steps in the state-of-the-art electrode production.

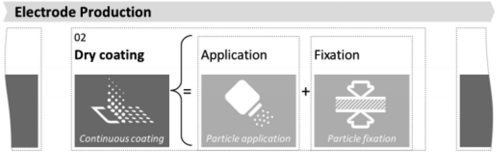


Fig. 2. Illustration on partial steps of dry coating technologies for manufacturing battery electrodes.

maturity of a particular technology and to allow consistent comparison of maturity levels between different technologies [70]. Besides the TRL, several other indicators exist to capture the maturity of technology or technology-related aspects. In more recent works, the general concept of technological maturity has also been applied to other technology-related subjects such as systems, integration, manufacturing, regulations, and markets. These efforts have resulted in additional readiness levels, such as manufacturing readiness level (MRL) [71], system (SRL) [72], integration (IRL) [73], regulatory (RRL), market (MRL) [74], acceptance (ARL), and organizational (ORL) [75]. Some of these have been used in combination and discussed for the inclusion of expected benefits in technology assessment.

Although various indicators exist for determining the developmental state of a technology [76], studies have reported their still isolated use and evaluation [77], noting difficulties when using IRLs or SRLs in the presence of uncertainty [78]. The high heterogeneity and complexity of technologies in the early stages of development further complicate the classification [79], [80]. Despite its development for decades, it seems that the TRL has remained widely accepted by many actors in the public and industrial research fields [77], [81]. However, the use of MRL instead of TRL is a point worth discussion in the context of selecting process technologies. MRLs are indicators that define the risk when the technology or process is mature and transferred into a system [71]. The key aspect for choosing which index to use is that manufacturing processes are not mature until product technology and design are stable [82]. With regard to the product technology of dry-coated electrode foils, still under development along with its process technology [83], it is advisable to use TRL to indicate the degree of maturity.

III. CASE OF LI-ION BATTERY CELL MANUFACTURING

A. *Process Description and Energy Consumption of the Manufacturing of Electrodes in Lithium-Ion Batteries*

Battery cell production usually starts with separate mixing of the anode and cathode materials to form slurries. For this, a liquid solvent is required, which is usually NMP [8]. The wet slurry is pressed through a slot die directly onto the metal foil (aluminum or copper) and then dried to remove the liquid solvent. The subsequent processes for electrode production are calendering, slitting, and vacuum drying. The state-of-the-art manufacturing process of electrodes for battery cells is illustrated in Fig. 1.

Afterward, the electrodes are ready to be stacked or winded into their final shape—the battery cell. This stage is referred to as cell assembly. It also includes placing the cell coil/stack into a housing and filling it with a (currently still) liquid electrolyte. Subsequently, the cell needs to be electrochemically activated and checked for irregular capacity drops to be fully operational. This final substep is referred to as cell finishing.

The identification of economically and ecologically more efficient viable alternatives is needed for the technological advancement of battery cell manufacturing. Especially in electrode production, the coating and subsequent drying step require large amounts of energy for the evaporation of the liquid solvent. This is also reflected in the high costs (over 20%) of this production step in the total costs of a battery cell [84]. To reduce the overall energy consumption in battery cell production, it is vital to reduce the energy consumption during electrode drying.

This can be achieved in the following three ways.

1) Using another, more efficient, drying technology.
2) Avoiding drying by using another cell chemistry.
3) Avoiding drying by using a dry coating process.

In terms of physics, Solution No. 1 has a low potential to save significant energy, and chemically, there is no reliable way to completely avoid using a solvent (No. 2). Thus, dry coating is the most promising way to save energy. Furthermore, toxic solvents can be eliminated, product quality can be improved, and the processing time can be decreased. Because of this, dry coating is seen as one of the holy grails for cleaner battery production. This was also confirmed by further research [8], [85], [86] and in industry by Tesla's CEO Elon Musk [4].

B. *Approaches to Realizing Dry Coating Technology*

In dry coating, the liquid solvent is replaced by a dry binder material. Instead of a wet slurry, a dry powder must usually be applied to the metal band. Here, two questions or rather challenges occur (see Fig. 2): "How does the powder mixture get onto the metal foil?" (Application) and "How can we ensure that the powder mixture remains on the metal foil and attains the desired state?" (Fixation).

In general, there are four major ways or mechanisms to realize dry coating, which may be summarized as follows:

1) powder application;
2) extrusion;
3) calendaring;
4) single-layer deposition; and
5) other

In *powder application*, gravity is used to let the powder trickle down onto the corresponding conveying medium [87], [88]. An additional auxiliary tool can be used to improve the homogenization of the material deposit and thus reduce undesirable property gradients on the electrode [89], [90]. In addition, electrostatic charges can be used to achieve initial adhesion to the metal foil. Here, a distinction can be made between the use of an electrostatic spray gun [85], [86], [91], [92] and an electrostatic fluidized bed [8]. Finally, another powder application method has been mentioned, which we refer to as the continuous molding method in this study. Here, hollow molds filled with electrode material are placed at regular intervals on the collector film and emptied afterward [93].

Extrusion-based solutions are hybrid solutions of wet and dry coatings. Instead of batch mixers, extruders are used, which are capable of transporting suspensions with a significantly higher content of solids [94]. The processing of suspensions with a solids content of over 90% instead of the usual 40%–70% is currently being researched and is already in initial industrial use [95]. However, there is still a small amount of liquid solvent used, which requires a minor drying effort, but significantly less drying than wet coating.

For both mechanisms, a subsequent *calendering* was necessary for particle fixation, where the electrodes were pressed together by heated rolls. There are processes in development in which powder is applied directly by a funnel-like device during calendering, making both the other named powder application processes obsolete [87], [88]. Thus, calendering can also be a standalone dry coating mechanism.

Further applicable mechanisms are physical and chemical vapor *deposition* (PVD and CVD). In PVD, the active material is coated as plasma in a single layer to a substrate, of which pulsed laser deposition (PLD) is an exemplar [96], [97]. In CVD, solid components from the gas phase are deposited on the substrate as extremely thin layers, even atomic monolayers, formed through chemical reactions. One variant of CVD is atomic layer deposition (ALD), which has already been applied in studies of the coating of electrode materials [98], [99]. Nevertheless, both processes have very low deposition rates and application rates.

Other processes include double flame spray pyrolysis (DFSP) and atmospheric plasma spraying (APS). In DFPS, the active material and conductive carbon black are dissolved in the precursors and simultaneously applied to a transfer layer in separate flame spray pyrolysis and then laminated onto a collector film [100]–[102]. The APS exhibits huge similarities but differs from DFSP by applying a very high flame temperature and a very high speed for the particles sprayed on the substrate. In general, APS offers advantages such as high flexibility, very good uniformity of the coating, and high adhesive strength [103].

Considering the technological variety of dry coating technologies mentioned above, this study conducts an extensive technology review to explore which technology is selected and for what reasons for integration in internal operational and/or development activities. Thus, dry coating technologies are benchmarked in terms of numerous selection criteria (also referred to as key performance indicators (KPIs)), such as their capability and readiness. This study paves the way for more advanced, sustainable production technology by revealing opportunities to significantly reduce the energy consumption of lithium-ion battery cell production.

IV. METHODOLOGY

To answer the question of how technology in its early developmental status can be selected, a qualitative approach based on a case study design was chosen for this study. A case study design is commonly used when the research question (RQ) involves both the analysis of contemporary issues and the need for explanations of *how* things manifest or proceed [104]. Therefore, we examined dry coating technologies for battery cell production to determine which technology is the most attractive in terms of the outcome of a selection process.

TABLE I
TECHNOLOGY SELECTION APPROACH AND REFERENCE TO CASE STUDY CHAIN OF EVIDENCE

Step No.	Description of the approach of the step	Linkage to chain of evidence	Section in study
1	Initial workshop for selection and prioritization of technology evaluation criteria	Case-Study Report	IV-A
2	Technology-related data acquisition out of various sources (publications, patents, project reports, interviews)	Case-Study Database	IV-B, V-A to V-C
3	Technology-related data evaluation via applying qualitative content analysis	Concepts and RQ	IV-C, V-D, VI
4	Final workshop for evaluation of decision alternatives and technology selection	Case-Study Report	IV-D

The case of dry coating technology is unique for several reasons. First, the topic itself is highly contemporary and of high economic relevance. This is because battery cell manufacturing is experiencing strong market growth expected to contribute to the transformation of the transportation and energy sectors [4]. In particular, the elimination of drying in electrode manufacturing has enormous cost and sustainability advantages [9]. Second, the case is suitable for investigating the influence of technological maturity on the technology selection process through the case study method because dry coating for electrode manufacture is overall at a precommercial stage. This allows for an exploratory, unbiased observation of the dynamics of technology selection [105].

In terms of research design, our investigation represents a single-case study in embedded design, investigating 15 different technological alternatives of dry coating of electrode foils as subunits in their respective technology selection process. Subunits in embedded design provide opportunities for a more comprehensive investigation and improve analytical insight into the overall case [104]. Case study-based approaches persist in the scientific literature because of their versatility, flexibility, and ability to investigate phenomena in detail using real-world examples [106]–[108].

The technology selection process applied to the subject of dry coating technologies within the scope of the case study follows a four-step approach (see Table I). This approach also refers to the case study's chain of evidence by clearly outlining its structure, demonstrating methodological reliability [104]. The chain of evidence lays out the ideal-typical structure of a case study, starting with the research procedure (Case Study Report), passing the creation of the database (Case-Study Database), ending with the interpretation (concepts), and answering the RQ.

In the first step of the technology selection approach, the problem of identifying suitable evaluation criteria for technology selection was addressed by applying the nominal group technique (NGT) [109]. In the second step, information research based on bibliometric data as well as expert interviews was conducted, and in the third step, it was evaluated via qualitative content analysis (QCA) [110]. In the fourth step, based on the typical methodological procedure of a multicriteria decision analysis (MCDA) approach [111], the intermediate and later the final state of the evaluation was validated in another round of interviews. Finally, the selection criteria defined from the first step were compared, and the implications were derived.

A. Initial Workshop for Selection and Prioritization of Technology Evaluation Criteria

Previous studies have substantiated the added value of interactive decision-making approaches. These approaches show high effectiveness and include qualitative aspects [112]. Thus, a structured workshop was held as a prelude to further conceptualization of the research project with the aim of deductive categorization [113], [114]. This refers to the methodology used in the thematic text analysis [115]. Since identifying criteria for the evaluation of technology are the basis for a sound technology selection decision [116], a structured aggregation of group judgments is performed by drawing on the method of NGT [109]. Previous research has shown that guided workshop formats are well suited for the discussion and definition of a structure for problem-solving [117]–[119]. Comparative methodological work recommends the use of NGT in research settings where possible interparticipant conflict is low and the consensus is urgently needed [120].

In a first workshop, the question was addressed, "Which characteristics are relevant to benchmark new battery cell production technologies related to electrode coating?" The workshop involved seven researchers and directors from a German battery cell factory. We considered the potential for conflict among workshop participants to be low because they were all part of the same institution. No conflicts of interest regarding technological preferences were apparent, and thus, the long-term success of the organization was the primary common goal. These participants combined academic backgrounds of science, engineering, and business management with a profound knowledge of battery cell manufacturing. The battery factory is planned to be scaled up to reach a production capacity (for electrodes) of up to 7.0 GWh battery capacity p.a. Comparison with the production capacity of industrial factories (e.g., SK Innovation, Georgia, USA, 11.7 GWh/a [121]; Northvolt Zwei, Salzgitter, Germany, 16 GWh/a [122]; and CATL, Erfurt, Germany, 14 GWh/a [123]) shows that the factory is of industrial scale and is state of the art.

The workshop itself covered the following three steps.

1) Relevant KPIs were collected individually and mutually.
2) KPIs were reviewed and clustered by the participants via group discussion.

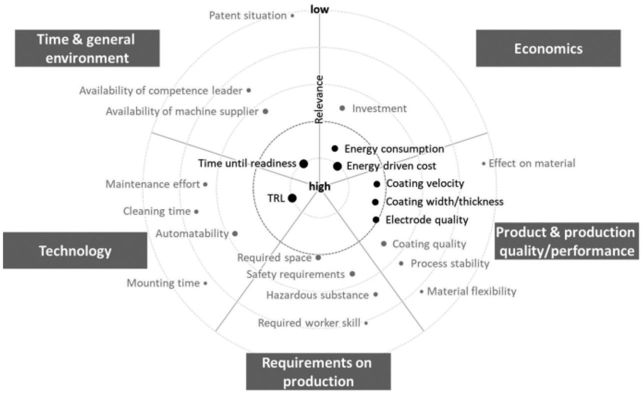


Fig. 3. Groups and KPIs to rate the electrode production, structured regarding their relevance (high to low).

3) The KPI relevance was determined through renewed group discussion.

As a result of the workshop, 40 KPIs were identified in total, which could be clustered into five major groups.

1) *Economics*: Clusters the KPIs that can be expressed through financial means.
2) *Product and production quality/performance*: KPIs that express how fast and well a product can be manufactured.
3) *Requirements on production*: The KPIs related to the (technical) production environment.
4) *Technology*: KPIs that describe nonproductive related parameters of the technology.
5) *Time and general environment*: Time and other aspects that affect the availability of technology.

In the five groups, the parameters were benchmarked related to their relevance (high to low) when assessing new production technologies or new coating technologies. Fig. 3 presents the comprehensive results.

It may be seen that seven individuals or four consolidated KPIs are rated as very important when benchmarking new coating technologies.

1) *TRL/time until readiness*: The time until the technology is fully applicable.
2) *Process performance*: The produced electrode area per time.
3) *(Energy) cost*: The required energy and cost per produced electrode area.
4) *Product quality*: The quality of the produced quality (e.g., homogeneity).

The methodological approach adopted is suitable for identifying evaluation criteria with a high likelihood of generalizability, especially for related processing industries, and thus to uncover which criteria are important for decisions on the further development of technologies at an early stage. By definition, the implementation must always be considered in light of both the technological object studied and the group of experts involved.

To rate these KPIs related to a certain coating technology, a reference is required. The reference here is the state-of-the-art industrial wet-coating production process. The reference parameters for today's wet coating are as follows.

1) *TRL:* Level 9 according to the NASA [70] and ISO [124]. Today, wet coatings are completely industrialized.
2) *Process performance:* The state-of-the-art coaters usually have a coating velocity of up to 80 m/min and a coating width of 750 mm, with no relevant limitations in coating thickness (two-sided).
3) *(Energy) cost:* The coater and dryer have a total nominal power of 1825 kWh. The cost of power differs strongly from the country in which production takes place.
4) *Product quality:* The coater should be able to produce a constant thickness of 250 μm and ± 2 μm when running at a nominal coating velocity [125].

B. Data Acquisition

In accordance with Fig. 3, the initial definition of the evaluation parameters for technology selection is followed by the collection of technological data. This step is carried out to build up the case study database—in other words, to develop a foundation of data for the technology selection process. Because case studies are known for their rich empirical descriptions of specific instances of a phenomenon, they are typically based on a variety of data sources [104]. Technology selection decisions require incorporating social aspects, which underlines the need to analyze multiple data sources. It is well-known that qualitative data afford insights into complex social processes that quantitative data cannot readily reveal [105]. The triangulation approach overcomes the problem of potential information asymmetry that occurs especially for technology in its early stages. This circumstance poses a more serious problem for other methods, such as surveys [126].

As a basis for the technology selection process, it is rather the evaluation of the workshops at the beginning and end of the process that comes into play. These were implemented through the methodology of direct observation [127] and documentation of the dialogue. The evaluation was conducted with respect to the concepts of prioritization and the data source raised in Section IV-C. To ensure objectivity, the evaluation process was carried out independently by three researchers from the field of technology management and processed in a subsequent critical discussion [128]. To avoid overall biases caused by single-source data within the development of the case study database, it is advisable to include multiple data sources and cross-compare them accordingly in the sense of triangulation [129]. The analysis processes academic publications, patent data, R&D projects, business reports, and insights from expert interviews to an overall picture of the respective electrode coating technologies.

In line with earlier work dealing with technology selection problems, a publication-based approach was also used to compile the basic database [130], [131]. The search procedure for the relevant secondary data was carried out using keyword-based search queries, in which the individual terms were linked together with Boolean operators. A list of the databases used and the corresponding search terms used can be found in Appendix I. The abstracts, short descriptions, and summaries of the hit list were manually checked for contextual relevance and then analyzed in detail. In addition to the defined search process outlined here, individual articles were manually added to the recommendation of interview partners. As a result of this procedure, several sources were obtained, of which 18 scientific articles, 15 patents, 19 research projects, and 6 business reports were analyzed in detail.

TABLE II
CHARACTERISTICS OF INTERVIEWEES AND THE FOCUS OF CONVERSATION DURING THE INTERVIEWS

Interviewees' characteristics	Interview focus	Interview subject	Number of interviews
Leading researchers from public R&D institutions	Technology-specific	First interview, broad inquiry regarding alternatives for dry coating technologies	7
		Second interview, focus on technology details	5
		Third interview, focus on technologies' integration capability	4
Technology experts from battery cell manufacturing industry	General	Interview on overall validation of work progress on dry coating technologies	1
		General activity on dry coating technologies, R&D status and technology activity	5

The effectiveness of this analysis step closely follows known conditions from scientific work for analyses of reviews, trend analyses, and forecasts. Thus, the availability of information is a conditional criterion for the quality and informative value of the data collection step, which functions well if technology-specific research work has already emerged from the field of public R&D, as in the case of the present study. This means that publications, publicly accessible project reports, and interviews can be prepared for analysis and evaluation. If the technologies in question have only been studied in industrial R&D, only patent data can be evaluated. Accordingly, a focus on the evaluation of patent documents is mandatory to include industrial R&D activities and ensure a comprehensive data basis.

To supplement the findings from the collected publications with detailed expert knowledge, 18 interviews were conducted with representatives from the fields of public and industrial research and development. The interviewees were carefully selected in the sense of pursuing purposeful sampling to most effectively utilize their wealth of knowledge (compare [132]). An overview of the characteristics, interview focus, and a number of interviews is presented in Table II.

The interviews were semistructured and based on a thorough literature review, using an interview guideline for R&D institutions (see Appendix II) and another shortened guideline for interviewees from industry (Appendix III), paying attention to IP sensitivity. The guideline structure is based on the initially given deductive structure (see Section Fehler! Verweisquelle konnte nicht gefunden werden) as well as on the preliminary results of the literature review. To verify the suitability of the interview guide, it was critically discussed in a group of three researchers beforehand. To improve external validity by iteratively adapting the interview structure [133], [134], the interviews followed an interactive refinement process. To ensure the reliability of the interview data [128], the interviews were generally conducted jointly by two researchers and a simultaneous recording of the interviewees' statements was made.

C. Data Evaluation

The evaluation of the collected data from various sources features aspects of qualitative and quantitative research and is therefore classified as a mixed-method approach, according to [132] and [135]. Typical components of qualitative research lie both in the deductive evaluation procedure and in the corresponding interpretation of technological selection criteria. The corresponding quantitative elements are the bibliographic source types and the assessment of the relevant technical metrics of the KPIs analyzed.

The evaluation followed a QCA-based approach. Within the coding process, the collected data were aligned with the evaluation categories from the initial workshop as part of a deductive, category-based approach [110]. In the later stages of the process, the evaluation became more inductive until information saturation effects occurred [136]. The concepts of prioritization and source type can be extracted from this inductive approach as influencing variables to be investigated throughout the selection process.

1) Prioritization of the evaluation variables of technologies regarding the general development status of technological use.
2) The consistency of technology selection with the initially determined evaluation variables reflects information asymmetry and different data sources.

The collected observations were aggregated in a matrix to compare the technology alternatives and evaluation criteria. To ensure an objective analysis, according to [137], the rating steps were carried out independently by two researchers and critically discussed afterward. The procedure for assigning the data to the coding or the evaluation criteria raised at the beginning of the study forces the researchers to engage in critical discussions. A strongly iterative procedure could be experienced so that the evaluations of technologies recorded later were compared with previously recorded technologies. Thus, classifications were reconsidered, and further facets of the expression of the evaluation criteria were subsequently added. The direct comparison of technological alternatives was effective and offered the advantage that individual gaps in knowledge could be identified immediately and eliminated in a targeted manner. If this was not possible due to a general lack of information, it was also applied consistently to the entire range of technologies surveyed. For example, information in the direction of assessing technological and economic efficiency at the system level is almost impossible to collect. However, this was largely because dry coating technologies are developed to a prototype stage largely in isolation, and their integration into a production system is still largely pending. We attribute high effectiveness to the evaluation step in assessing technology alternatives based on the preceding descriptions.

D. Final Workshop for Technology Evaluation and Selection

For the fourth step of the technology selection approach, a roundtable discussion was held, involving the same group of researchers and leading employees of the battery cell factory from the initial workshop. We chose an MDCA-based methodological approach, as it is well suited for analyzing group decisions in work environments [111], [138]. According to the idea of synergy, decisions made collectively also tend to be more effective than those made by a single individual [139]. Methodological problems may arise due to group polarization and biases, which cause some group decisions to be more extreme than the decisions of their individual members [140]. However, for the application in the case presented here, the aim is to validate the elaborated content from a group perspective rather than from an individual perspective. Therefore, possible group interaction effects did not constitute an exclusion criterion for its application. The workshop included the following content aspects, as per [111].

Clarification of the decision context and the identification of group members.

1) Explication of decision objectives.
2) Generation of decision alternatives.
3) Elicitation of preferences.
4) Evaluation of decision alternatives.
5) Synthesis and communication of decision recommendations.

V. RESULTS AND DISCUSSION

A. Overview of All Identified Dry Coating Technologies and Benchmarking of Those

In this study, the TRL was used as a quantification indicator for the level of technological development (see Section IV). Because the TRL comprises a fixed measuring scale between TRL 1 and TRL 9 [124], the classification takes place by checking which requirement parameters for each technology are valid. The list of identified TRLs is given in Table III. The sources of each technology are presented in Appendix IV.

The classification of TRLs is challenging because each technology can only be rated qualitatively. This must be considered when assessing the results of this study. Deviations within the range of the ±1 level scale were possible. Nonetheless, the approximated maturity of these technologies is valid. However, the benchmark shows that most dry coating technologies are in an early stage of development, with a TRL lower than 4. Only four identified dry coating technologies have a TRL of 4 or larger, and thus, a chance to become industrialized in this decade. The most advanced dry coating technologies are free-standing electrode fabrication and direct calendering. Both technologies are discussed further in Section IV-B.

Regarding the process performance, Table IV reveals whether the dry coating technologies have the potential to surpass the

TABLE III
RATING OF DRY COATING TECHNOLOGIES IN TERMS OF THEIR TRL

Group	Technology	TRL	Reason for rating
n/a	Wet coating (reference)	9	Technology is applied at large scale in industry
Powder application	Electrostatic fluidized bed coating	4	Successful experiments in technical center Funding exists to reach TRL 6 in 2023
	Electrostatic spraying	3	Advanced experimental proof of concept
	Continuous molding method	2	Technology concept formulated
	Brush application	4	Successful experiments in technical center Funding exists to reach TRL 6 in 2023
	Planarsieve application	3	Advanced experimental proof of concept
Calendering	Direct calendering	5	Technology is validated and partly demonstrated in relevant environment
	Free-standing electrode fabrication	6	Technology demonstrated in relevant environment (for super caps)
	Hot melt extrusion process	2	Technology concept formulated
Extrusion	Extrusion-based coating	3	Experimental proof of concept Funding exists to reach TRL 5 until 2023
Single Layer Deposition	Atomic Layer Deposition	3	Experimental proof of concept
	Pulsed Laser Deposition	3	Experimental proof of concept
	Sputtering Deposition	3	Experimental proof of concept
Other	Atmospheric plasma spraying	2	Technology concept formulated
	Double flame spray pyrolysis	3	Experimental proof of concept Lab validation is scheduled
	Dry pressing	2	Technology concept formulated

TABLE IV
RATING OF DRY COATING TECHNOLOGIES IN TERMS OF THEIR PROCESS PERFORMANCE POTENTIAL, IN COMPARISON TO THE STATE-OF-THE-ART WET COATING

Group	Technology	Rating	Reason for rating
n/a	Wet coating (reference)	n/a	Technology is state of the art in industry
Powder application	Electrostatic fluidized bed coating	0	No speed limitation by drying But: particle drift is new velocity bottle neck
	Electrostatic spraying	-	No speed limitation by drying But: large process chambers are new bottle neck
	Continuous molding method	+	No speed limitation by drying
	Brush application	+	No speed limitation by drying Easier cleaning process
	Planarsieve application	+	No speed limitation by drying Easier cleaning process
Calendering	Direct calendering	+	No speed limitation by drying
	Free-standing electrode fabrication	-	No speed limitation by drying But: due to physics probably less coating velocity
	Hot melt extrusion process	0	No speed limitation by drying But: many process steps
Extrusion	Extrusion-based coating	+	No speed limitation by drying
Single Layer Deposition	Atomic Layer Deposition	--	No speed limitation by drying But: extreme low coating speed
	Pulsed Laser Deposition	-	No speed limitation by drying But: very low coating speed
	Sputtering Deposition	-	No speed limitation by drying But: low coating speed
Other	Atmospheric plasma spraying	?	Not enough information available for a reliable rating
	Double flame spray pyrolysis	+	No speed limitation by drying Process can be controlled well
	Dry pressing	?	Not enough information available for a reliable rating

state-of-the-art "wet coating" technology. It must be emphasized that, here, only the potential is rated when the technology is theoretically at TRL 9, and not the performance on today's low TRL, while technology is still in development. The following rating was used:

++ Much higher potential than the reference (5 points)
+ Higher potential than the reference (4 points)
0 Same potential than reference (3 Points)
- Lower potential than the reference (2 points)
– Much lower potential than the reference (1 point).

The coating velocity in wet coatings is usually limited by the required size/length of the continuous dryer. When the coating velocity is increased, the length of the continuous dryer must be increased. Each velocity increase of 1 m/min requires about 1 m added dryer length. Thus, most dry coating technologies can surpass wet coating, as no coating velocity limiting dryer is necessary. However, there are also dry coating technologies, such as deposition-based technologies, which have a low process performance owing to their physics. Table V shows the cost-saving potential of the identified dry coating technologies, especially in terms of their energy-saving potential, as this is the major cost driver in coating and subsequent drying.

All dry coating technologies have the advantage that no drying downstream of the coating step is required, and substantial energy cost can be saved, except for extrusion-based coatings.

TABLE V
RATING OF DRY COATING TECHNOLOGIES IN TERMS OF THEIR (ENERGY) COST SAVING POTENTIAL, IN COMPARISON TO STATE-OF-THE-ART WET COATING

Group	Technology	Rating	Reason for rating
n/a	Wet coating (reference)	n/a	Technology is state of the art in industry
Powder application	Electrostatic fluidized bed coating	+	No energy consumption for drying Less investment cost
	Electrostatic spraying	+	No energy consumption for drying Less investment cost
	Continuous molding method	+	No energy consumption for drying
	Brush application	+	No energy consumption for drying Less investment cost and personal requirements
	Planarsieve application	?	Not enough information available for a reliable rating
Calendering	Direct calendering	+	No energy consumption for drying
	Free-standing electrode fabrication	+	No energy consumption for drying Less investment cost
	Hot melt extrusion process	-	No energy consumption for drying But: High energy requirement for melting
Extrusion	Extrusion-based coating	0	Reduced energy consumption for drying But: less savings in investment cost
Single Layer Deposition	Atomic Layer Deposition	-	No energy consumption for drying But: high investment cost and quality demands
	Pulsed Laser Deposition	-	No energy consumption for drying But: high investment cost and quality demands
	Sputtering Deposition	-	No energy consumption for drying But: high investment cost and quality demands
Other	Atmospheric plasma spraying	?	Not enough information available for a reliable rating
	Double flame spray pyrolysis	0	No energy consumption for drying But: high cost for required solvent
	Dry pressing	+	No energy consumption for drying Less investment cost

TABLE VI
RATING OF DRY COATING TECHNOLOGIES IN TERMS OF THEIR PRODUCT QUALITY POTENTIAL, IN COMPARISON TO STATE-OF-THE-ART WET COATING

Group	Technology	Rating	Reason for rating
n/a	Wet coating (reference)	n/a	Technology is state of the art in industry
Powder application	Electrostatic fluidized bed coating	0	Equivalent electrochemical properties
	Electrostatic spraying	+	Higher mechanical strength Slower capacity loss of battery cell
	Continuous molding method	0	Equivalent electrochemical properties
	Brush application	0	Equivalent electrochemical properties
	Planarsieve application	0	Equivalent electrochemical properties
Calendering	Direct calendering	0	Equivalent electrochemical properties
	Free-standing electrode fabrication	+	Lower contact resistance Extended lifetime
	Hot melt extrusion process	0	Equivalent electrochemical properties
Extrusion	Extrusion-based coating	+	High homogeneity and less porosity
			Hardly any binder migration
Single Layer Deposition	Atomic Layer Deposition	+	Improved electrochemical properties regarding cycle stability and capacity
	Pulsed Laser Deposition	+	Significant improved electrochemical properties
	Sputtering Deposition	+	Improved electrochemical properties
Other	Atmospheric plasma spraying	+	Improved electrochemical properties
	Double flame spray pyrolysis	+	High homogeneity and improved layer stability
	Dry pressing	+	High homogeneity and bending flexibility

Here, a very small amount of solvent is still used, and thus, minor drying is required. In addition, for the hot melt extrusion processes, additional energy needs to be provided as the inserted material must be melted. Moreover, during the powder fixation step, which is usually accomplished by pressing or rolling, heat must be induced to melt the binder particles in the powder mixture. Further energy is required for this step; however, this sums up to significantly less than the evaporation of the solvent in wet chemical processing would require. On the one hand, the deposition technologies have a low energy consumption, on the other hand, the investment and, thus, the depreciation cost are very high. In addition, these technologies require high-quality standards in terms of the environment and material, which also increases the running cost. Table VI shows the potential of the identified dry coating technologies in terms of the achievable product (electrode/cell) quality.

All dry coating technologies have the potential to achieve the same or even better electrode quality in comparison to state-of-the-art wet coatings. The proof that novel processes can produce electrodes of equal or better quality is generally already given to the research teams as a prerequisite for the publication of studies. For most dry coating technologies, the chemical properties or the homogeneity of the active materials are improved, which also impacts the later cell properties.

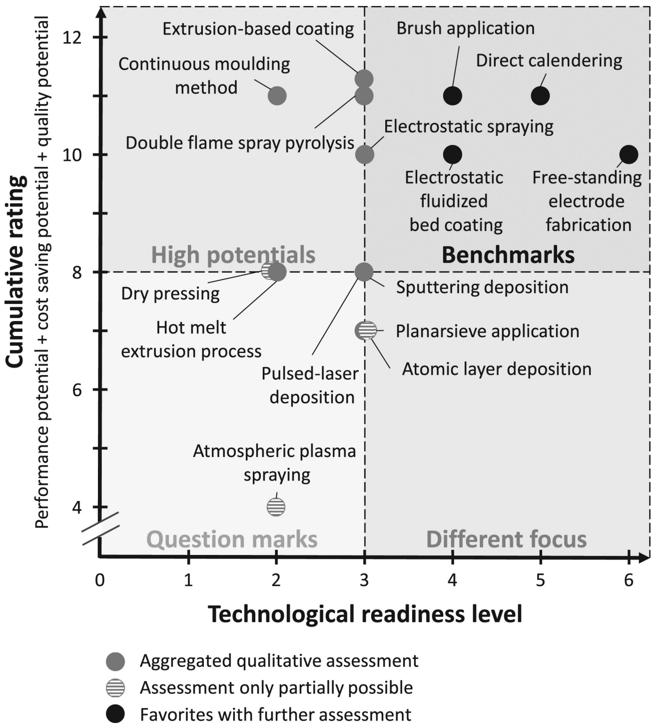
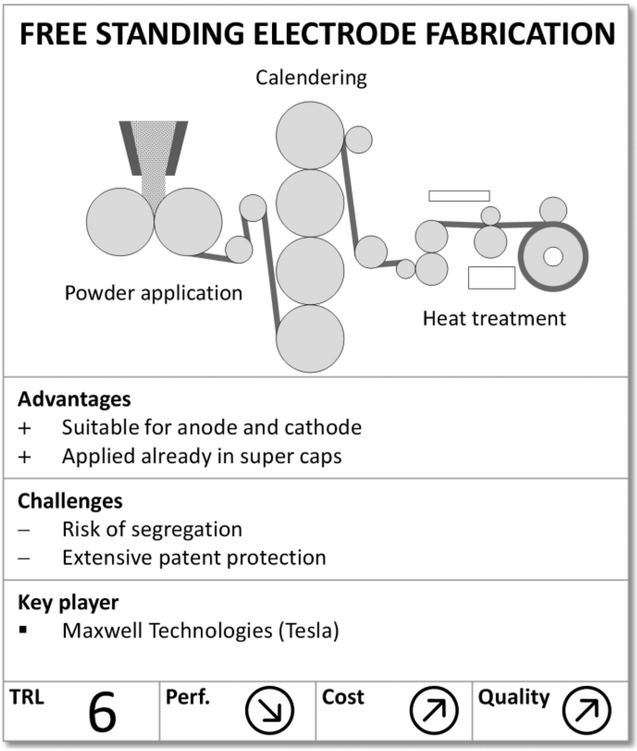


Fig. 4. Attractiveness of dry coating technology in terms of TRL and overall cumulative rating.



FREE STANDING ELECTRODE FABRICATION

Advantages
+ Suitable for anode and cathode
+ Applied already in super caps

Challenges
– Risk of segregation
– Extensive patent protection

Key player
▪ Maxwell Technologies (Tesla)

TRL	6	Perf.	↘	Cost	↗	Quality	↗

Fig. 5. Technology fact sheet of "free standing electrode fabrication" (process sketch based on [87]).

Fig. 4 shows the identified dry coating technologies in a performance portfolio, where the *x*-axis shows the TRL and the *y*-axis shows the cumulative rating of the KPIs. The latter was calculated by the sum of the process performance potential, energy cost-saving potential, and product quality potential.

B. Detail Analysis of Most Promising Dry Coating Technologies

The four dry coating technologies already have a higher TRL and high overall performance potential. These four dry coating technologies are as follows:

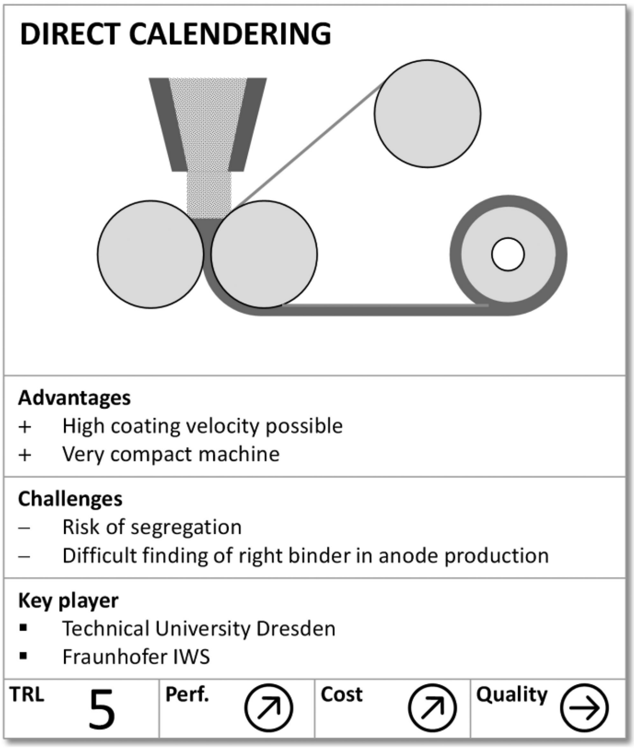
1) free standing electrode fabrication;
2) direct calendaring;
3) brush application; and
4) electrostatic fluidized bed coating.

These will be analyzed in detail in the following sections. For each technology, a fact sheet is shown that summarizes all important technology information.

The dry coating process for the "free standing electrode fabrication" (see Fig. 5) is a process originally developed by Maxwell Technologies for the production of super caps [87]. According to the description in Sections II-B, it is a dry coating process that performs direct application and fixation of the powder mixture in one step. A powder mixture of active material (anode or cathode material), conductive additive material, and binder material is considered to form a continuous, self-supporting, dry-coated electrode film, which can be wound up in roll form. The finished electrode film is then laminated to the current collector in a further step to produce an electrode ready for cell production.

According to Tesla's CEO Elon Musk at his recent presentation on Tesla Battery Day 2020, the manufacturing technology developed by Maxwell cannot be transferred 1:1 for LIB manufacturing [4]. According to the company's information, the technology is currently undergoing plant revision until it is ready for series production. Nevertheless, we estimate that the time to this point is closer than for other dry coating processes because the anode and cathode materials have already been successfully processed and a wealth of experience has been gained since the patent application for the process was filed in 2004 to produce super caps. Currently, the challenge is to adapt the process to the requirements of electrode manufacturing for Li-ion batteries.

There is a good cost reduction potential for the process, as the energy consumption is estimated to be significantly lower owing to the complete elimination of the drying step. The process performance is currently still a weak point of the process, as it will probably be difficult to achieve coating speeds similar to those of the reference process of 80 m/min. The reasons for this are to be seen in the necessary sensitive handling of the free-standing electrode film, which must be placed on the transport medium for further processing in a subsequent step. With regard to product quality, promising results have already been reported (higher energy density, improved performance especially with high loads, and extended service life) owing to the low contact resistance on the electrode surface, which is inherent in the process [87]. In total, it can be said that free-standing electrode fabrication is probably today´s most mature dry coating technology and will be used in industrial production within the next few years.



DIRECT CALENDERING

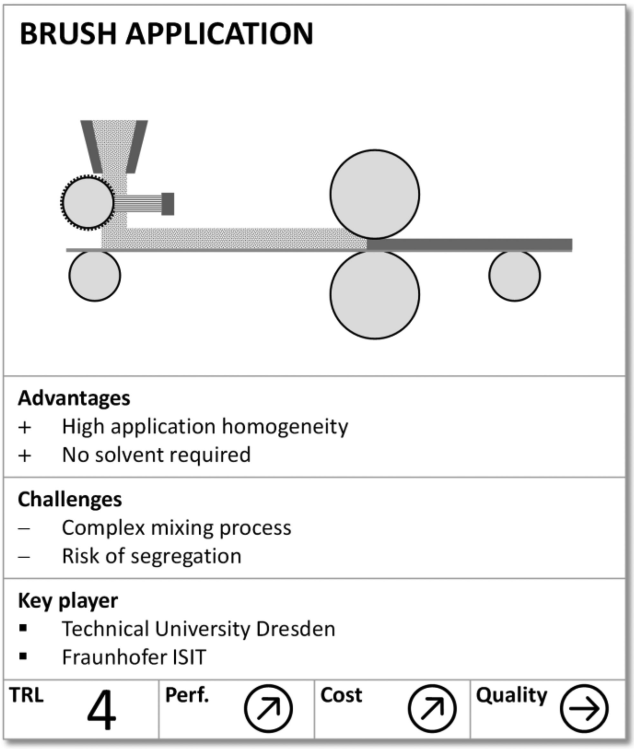
Advantages
- + High coating velocity possible
- + Very compact machine

Challenges
- – Risk of segregation
- – Difficult finding of right binder in anode production

Key player
- ▪ Technical University Dresden
- ▪ Fraunhofer IWS

TRL	Perf.	Cost	Quality
5	↗	↗	→

Fig. 6. Technology fact sheet of “direct calendering” (process sketch based on [88]).



BRUSH APPLICATION

Advantages
- + High application homogeneity
- + No solvent required

Challenges
- – Complex mixing process
- – Risk of segregation

Key player
- ▪ Technical University Dresden
- ▪ Fraunhofer ISIT

TRL	Perf.	Cost	Quality
4	↗	↗	→

Fig. 7. Technology fact sheet of “brush application” (process sketch based on [90]).

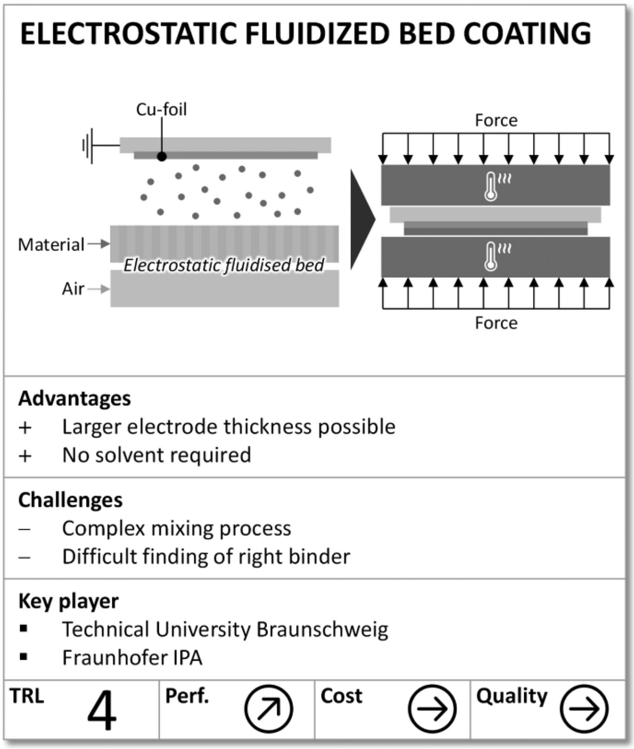
The *direct calendering* (see Fig. 6) process exhibits great similarities with Maxwell’s process, as presented previously. Nevertheless, there are a few crucial differences between the two processes. First, dry powder material is compressed into an electrode film by means of two heated rollers and (in contrast to Maxwell’s process) applied directly to the current collector foil without the electrode film leaving the laminating roll in the meantime [88]. This allows significantly higher coating speeds because the formation of a sensitive free-standing electrode film is prevented. In other words, the focus of the Maxwell process is on the pressing of the powder mixture, while the focus of the direct calendering process is on the direct coating.

The development status of the technology was estimated with a TRL of 5, which is slightly lower than that of the previously presented process. The reason for this is that the technology was developed in the past, mainly for the processing of cathode materials, and the production of anode material has recently been added as a research subject (however, as we were told, with promising results). Furthermore, it is positive to note that patent protection exists and that initial technology commercialization activities have already been undertaken [88], [141]. The cost-saving potential was estimated to be similar to that of the free-standing electrode film process. A decisive advantage over this is seen in potentially high coating speeds (even higher than with the conventional wet-chemical process). The interviewees stated that a coating speed of 100 m/min is quite realistic. With regard to product quality, it can be stated that electrodes of roughly the same quality (compared to the reference process) can be processed. Currently, the slight fluctuations in coating thickness (±5%) are being reduced.

In addition to the double-sided coating, the aim of the future process optimization is to eliminate a final calendering step to realize further cost reduction potential. Finding the ideal type of (PTFE) binder for anode production is also on the agenda for the immediate future, as the use of binders and their properties have a strong influence on the final electrode quality.

The *brush application* (see Fig. 7) is a powder application method in which the powder (consisting of active material, conductive additive, and binder) is applied onto a needle roller and is then brushed out so that the powder trickles onto the current collector. The applied powder is then directly thermomechanically fixed and compacted on the film without any further transfer steps.

Brush application is a technology that is being further developed as part of the ÖkoTrop project in the ProZell cluster of the German Federal Ministry of Education and Research. The current development status is assessed by the researchers themselves as TRL 4 with the aim of developing this further to TRL 6 by 2023. Accordingly, preliminary pilot plant trials have already been carried out, but integration into the overall process chain has not yet been implemented. The current focus has been on the processing of cathode materials. Potential cost savings can be identified in terms of reduced energy consumption, reduced investment costs in machine and factory technology, and fewer personnel required (according to estimates by experts involved, 25%–40%) to operate the process technology. Now, coating speeds of 20 m/min at a width of 350 mm can already be achieved



ELECTROSTATIC FLUIDIZED BED COATING

Advantages
+ Larger electrode thickness possible
+ No solvent required

Challenges
– Complex mixing process
– Difficult finding of right binder

Key player
- Technical University Braunschweig
- Fraunhofer IPA

TRL 4	**Perf.** ↗	**Cost** →	**Quality** →

Fig. 8. Technology fact sheet of “electrostatic fluidized bed coating” (process sketch based on [8]).

with the powder coating process. This is, of course, significantly lower than in the reference process, but can be justified with the current TRL 4 and has good prospects of being scaled up in the upcoming years. A previously determined drying step was no longer present. Electrodes with electrochemical properties equivalent to those of the reference process have already been produced on a smaller scale.

For the integration capability into the overall manufacturing process, the mixing process upstream of the coating process and the conditioning of the respective particles is clearly moving into the focus of interest because its control is highly complex and has a major influence on the coating properties. For the processing of anode mixtures, for example, the mixing process would have to be done in two steps (first, the binder and carbon black are processed and then the active material because the graphite is susceptible to fracture). In addition, the use of an exhaust filter in the area from mixing to fixing is necessary to meet workplace safety guidelines. Because brush application is a technical solution for particle application, downstream particle fixation is, in principle, possible using different methods. Interview partners have high porosities after particle application, which must be considered in the design of the downstream fixation and calendering steps. Further challenges for the further development of the technology lie in the development of a sharp scattering edge during powder application.

The *electrostatic fluidized bed coating* (see Fig. 8) is another powder application process, which involves passing the collector film over a fluidized bed and electrostatically covering it with active materials, conductive additives, and binders. The applied powder is thermomechanically fixed and compacted on the film directly after the application of the powder mixture without a further transfer step.

TABLE VII
EFFECT OF DIFFERENT DRY COATING INDUSTRY SHARE RATIOS ON THE ANNUAL SAVED ENERGY AND CO_2 EMISSIONS IN 2030

Industry share in 2030 [%]	Saved Energy p.a. [GWh]	Reduced CO_2-eq emissions p.a. [mio. t]	Reduced € energy cost p.a.* [mio. €]	Reduced € CO_2 emission taxes p.a.** [mio. €]
100	17,312	4.76	173.12	261.80
25	4,328	1.19	43.28	65.45
10	1,731	0.48	17.31	26.18
5	866	0.24	8.66	13.09

Electrostatic fluidized bed coating is another technology that is being further developed in the ÖkoTrop project. The current development status is assessed by the researchers involved as TRL 4, with the aim of further developing it to TRL 6 by 2023. Accordingly, preliminary pilot plant trials have already been conducted, and a roll-to-roll process should be implemented in the course of the project. So far, the focus has been on the processing of anode materials. An extension of the application of cathode materials has also been envisaged. Patent publications that protect process technology are already accessible [142]. Similar to the brush application, cost savings can be achieved by lower energy consumption, smaller and less expensive machinery, and a reduction in floor space requirements by half. The process performance is similar to that of the brush application, with a throughput of 20 m/min at a coating width of 250 mm achieved to date. Instead of the drying step, the degree of particle migration is a new speed determining step. Electrodes with electrochemical properties equivalent to those of the reference process have already been produced on a smaller scale.

Integration into the process chain for battery cell production is similar to that of brush application. The decisive factor is the selection of an appropriate binder and processing in the mixing phase. What distinguishes electrostatic fluidized bed coating from other coating processes is the coating from below, which means that there must be no deflection roller in the process from powder application to fixing.

C. Potential Effect on Global Energy Savings

It can be assumed that through the dry coating technology, the energy consumption for drying after coating can be eliminated almost completely. If the requirements for vacuum drying and drying rooms are affected, it cannot be said yet. Likely, both are still required owing to chemical restrictions regarding the nickel components in the electrode. However, the use of vacuum dryers may be reduced. However, a major question is, when industrial dry coating processes with TRL 9 are ready to enter the market and how fast these substitutes the state-of-the-art wet coating processes. Table VII shows the annual saved energy and related CO_2 emissions in 2030 for different industry shares of dry coating technologies, regardless of the type of dry coating technology used.

A dry coating industry share of 100% by 2030 is unlikely. The reason is that machinery, which is bought today for millions of euros, is most likely to run in production for the next 5–10 years unless a major overall cost advantage can be realized by new machinery/technology. However, even when only 10% of the battery cell manufacturer is going to use dry coating technologies in 2030, 480 000 tons of CO_2 emissions could be saved annually. As an example, when considering the energy cost and CO_2 emission cost of Germany, this means an annual savings of € 45 million.

D. *Discussion of Observations From the Technology Selection Approach*

Generally, the case study provided insight into the current status of dry coating technologies for pre-commercialization. None of the identified technologies were beyond the prototype stage of TRL 6. The following was observed while analyzing the concept of prioritization of evaluation variables with regard to technological development. During the initial workshop, the focus was on factors that reflect the basic usability of technologies (TRL) and on the positions of operating costs (energy costs). More generally, it can be stated that the evaluation is initially based on the technologies' main purposes. In the case of state-of-the-art coatings, this is primarily the elimination of solvents and thus savings in energy consumption and costs. In addition, the strategic fit of the TRL, as well as the fulfillment of essential requirements such as product quality (coating quality) are considered. Mohanty *et al.* [145] confirmed this finding by grading strategic, tactical, and monetary weighting in decreasing priority. During subsequent workshop sessions, we observed a shift toward the focus of the evaluation criteria in technology selection. Factors that are of greater importance for the integration of technologies into the operational and manufacturing processes subsequently gain significance (see also Fig. 3). This is consistent with earlier studies on the dependencies of the evaluation criteria in the context of technology selection [146].

Concerning the concept of consistency of technology selection according to different data sources, we could not observe any decisions in favor of or against alternatives. This can be attributed to the fact that a higher level of information uniformly reveals strengths and weaknesses. However, we observed the risk of personal technology preferences. This resulted from direct exchange via interviews with technology owners and can be explained by the development of mutual trust [147]. Thus, we recommend that data collection and evaluation be carried out by separate technology management teams.

VI. CONCLUSION

The aim of this study was to answer the following questions: what is the most promising dry coating technology and how to identify it? Using technology screening and multistage interviews with experts, 15 different dry coating technologies could be identified. By benchmarking these technologies, four different dry coating technologies could be identified, which show a high potential for commercialization within the next few years. These are namely "free standing electrode fabrication," "direct calendering," "brush application," and "electrostatic fluidized bed coating." All technologies have the potential to eliminate the energy-intensive drying step in today's wet coating. By use of dry coating up to 4.76 million tons of CO_2, 175 million € of energy expenditure and 260 million € of CO_2 emission taxes could be saved in 2030 per year. Thus, it can be said that dry coating is a sensible and realistic approach to reduce energy consumption and cost in battery cell production.

According to the second part of the RQ, we followed a 4-step approach based on the methods of NGT for defining the criteria of technology selection, QCA for data analysis and evaluation, and MCDA for the final validation and selection. We conclude that under the condition of access to technology experts, this approach is especially suitable for technologies in an early stage of development because information deficits may be successfully compensated by the variety of different information sources and by their qualified assessment by technology experts.

Our study provides the first cohesive comparative overview of dry coating technologies for the electrode production of Li-ion battery cells in terms of quality, cost, and development. Our work recapitulates previous R&D work and reveals the current technological intermediate status for the development of dry coating technologies. In a broader sense, we add to the prevailing literature on decision making in the field of emerging technology management by presenting a viable and generalizable mixed-method based four-step solution path and illustrating how decisions for the selection of technologies in the early developmental stage can be made under uncertainty. We believe that the process can be generalized, at least for technologies that do not originate exclusively from industrial research environments. Companies usually pursue a closed innovation approach for potential future core technologies, which strongly inhibits the procurement of information and the willingness of experts to talk. Highly conflictual constellations would complicate the initial and final steps of criteria identification and final evaluation. With regard to the subject matter focus, we would see direct transferability (also, for example, of the concrete, elaborated evaluation criteria) to other process technologies from the chemical, food, electronics, and other manufacturing industries. In the case of a potential focus on product technologies, it is conceivable that the evaluation variables initially tend to shift away from TRL and energy costs toward sustainability aspects such as life cycle perspective, recyclability, and resource availability. The subsequent methodological steps are then based on this.

Thus, this study extends the "toolbox" available to managers and policy makers to develop, transfer, and integrate new technology-based innovations responsibly and successfully. Furthermore, the insights drawn from the research are relevant from a managerial perspective, since successful technology selection at an early stage enables the early development of competitive advantages.

The results of our study also provide various practical contributions to stakeholders from research, industry, and politics. Actors from research will be enabled by the findings of our study to critically compare the processes they have researched and to identify important unique advantages. Actors from industry will be made aware of our study of technological alternatives (if not yet known) along with corresponding potential development partners regarding the coating of electrode foils for battery cell production.

The main limitation of the analysis lies in its applied methodological approach for data collection and analysis. The research presented here takes the form of a single-case study with the aim of analytically generalizing its conclusions (especially those drawn from its methodological approach to solving the RQ). Further application of the proposed approach to other cases in similar or different settings would contribute to further understanding of method suitability for technology selection. Although we have endeavored to the best of our knowledge to consider all currently available alternatives regarding dry coating technologies and to evaluate them objectively, it cannot be guaranteed with absolute certainty that the information base is complete. The reason for this may be that the rate of patented process innovations is significantly lower than that of product innovations and is thus handled as industry secrets. Furthermore, as mentioned above, it is generally challenging to create a consistent information base for emerging technologies. Another limitation is that the geographical focus of the interviews was on a national/European group of experts, which might be a limiting factor due to sample quality.

Due to these limitations, opportunities arise with further research to follow up on this article’s findings. Thus, using a similar methodological approach represents the opportunity to analyze further process steps for battery cell production to stimulate step-by-step comprehensive techno-economic optimization work on cell processing. Furthermore, subsequent studies in a more quantitative, narrower framework could deal with the investigation of technical phenomena that challenge the benchmark presented here and derive specific research goals for the further development of respective process technologies.

APPENDIX I
SEARCH TERMS APPLIED IN DIFFERENT DATABASES FOR THE COLLECTION OF SECONDARY DATA

Data Type	Database	Search Terms
Scientific publications	Scopus	TITLE-ABS-KEY (manufacturing AND of AND electrodes AND for AND li-ion AND batteries)
Patent data	Espacenet	solvent-free dry coating electrode lithium ion battery
R&D projects	CORDIS	(/article/relations/categories/collection/code='brief' OR (/result/relations/categories/collection/code='deliverable','publication' OR (/result/relations/categories/collection/code='pubsum' OR contenttype='project'))) AND ('electrode' AND 'lithium-ion' AND 'battery')
Business reports	Google	solvent-free dry coating electrode lithium ion battery

APPENDIX II
GUIDELINE USED TO CONDUCT THE INTERVIEWS WITH THE EXPERTS FROM PUBLIC R&D INSTITUTIONS

Topic	Question
Technology description	How would you briefly describe the technology in 3 sentences?
	For which battery technology is the process suitable?
Key experts	In what context are you involved with the technology?
	Which partners are involved in the development?
	Which other institutions do you know that deal with this technology alternative?
Development status	How would you assess the state of development, what technological maturity does the process currently have?
	What are the biggest advantages of the technology?
	What are the biggest challenges at present and in the long term?
Production	What does the process chain of electrode coating with your process look like?
	a. How is the material applied?
	b. How does it differ from the coating in classical electrode production?
	c. How does it differ from other (dry) coating technologies in battery production?
	Process performance
	a. Coating speed and width
	b. (OEE) - operating time vs. set-up and cleaning times, reject rate,
	c. Capacity/throughput per year
	d. Process robustness
	Requirements for the production environment
	a. Area requirements
	b. Environmental Compatibility
	c. Other infrastructure requirements
	d. Drying room / Micro-Environment
Profitability	How do the operating costs compare to current processes? (qualitative)
	Where are the greatest savings potentials?
	Energy consumption
	Maintenance
	Material costs
	Resources
	Personnel expenses
	Estimate of investment costs
Product quality	Does the process influence the product quality compared to today's state-of-the-art LIB? (qualitative)
	In which characteristics do improvements/disadvantages occur today or can be expected in the future?
	a. Porosity
	b. Homogeneity
	c. Coating thickness
	d. Surface loading
	e. Specific energy density
	f. Capacity
	g. Mechanical stability
Technology Transfer	How would you estimate the further effort (time and costs) until marketability?
	How easily can the technology be integrated into a pilot production line?
	How easily can the technology be integrated into a standard production line?
	What are your plans for the further development of the technology?
Further technology alternatives	Which other technology alternatives are known to you?
	How can these be characterized and how do they differ?
	Is the variety of technology alternatives still growing? Or do you assume which one of the processes currently under development will establish itself as state of the art in the next few years?

APPENDIX III
GUIDELINE USED TO CONDUCT THE INTERVIEWS WITH EXPERTS FROM INDUSTRY

Topics	Interview focus
General activity on dry coating technologies	Does your company already carry out R&D activities for the dry (i.e. solvent-free or nearly solvent-free) coating of electrodes or are they planning to do so in the future?
R&D status	Has the development work already progressed so far that products can be offered?
Technology focus	(If it is possible to make a statement from an IP-legal perspective) Within the scope of which technological process, products are being developed?

APPENDIX IV
ASSIGNMENT OF SOURCES TO RESPECTIVE DRY COATING TECHNOLOGIES

Dry coating technologies	Sources
Wet coating (reference)	[148, 149]
Electrostatic fluidized bed coating	[8, 150]
Electrostatic spraying	[85, 86, 91–93]
Continuous molding method	[93]
Brush application	[90]
Planarsieve application	[89, 151]
Direct calendaring	[88, 141, 152, 153]
Free-standing electrode fabrication	[87, 154]
Hot melt extrusion process	[155]
Extrusion-based coating	[94, 156]
Atomic Layer Deposition	[98, 99, 157]
Pulsed Laser Deposition	[96, 97, 158]
Sputtering Deposition	[159, 160]
Atmospheric plasma spraying	[103]
Double flame spray pyrolysis	[100–102]
Dry pressing	[161]

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