



Insights into dry battery electrode manufacturing: Unveiling the patent landscape

Tim Greitemeier^{a,*} , Simon Lux^{a,b}

^a University of Münster, Institute of Business Administration at the Department of Chemistry and Pharmacy, Leonardo Campus 1, 48148 Münster, Germany

^b Fraunhofer Research Institution for Battery Cell Production (FFB), Bergiusstrasse 8, 48165 Münster, Germany

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ABSTRACT

The advent of lithium-ion batteries (LIBs) has resulted in increased requirements and demands, which has in turn led to the upscaling of manufacturing to gigafactory scale. At this scale, energy consumption and production costs represent crucial targets for innovations. Both targets are simultaneously addressed by dry battery electrode (DBE) manufacturing, through the elimination of toxic solvents and the subsequent omission of the energy-intensive drying procedure. Additionally, it has the potential of improved performance and compatibility towards the production of all-solid-state batteries (ASSBs) compared to solvent-based coating. Prior research either focuses on laboratory-scale applications or summarizing research advancements. Consequently, a gap regarding the application of data science analysis in the field of dry coating remains in literature. To fill this gap, a dataset comprising the four primary DBE manufacturing technologies, devices and materials is subjected to an in-depth analysis. This analysis addresses the historic evolution of each technology and the underlying processes, thereby identifying the calendaring mechanisms that employ binder fibrillation as the major fields of interest, offering the biggest revenue. The breakdown by region and assignee identified the United States, particularly Tesla and Maxwell, as the pioneering actor in free-standing calendaring of DBEs, both in terms of total number and impact of the portfolio. However, the recent expiration of the initially patented free-standing calendaring technology by Maxwell has paved the way for several other companies to innovate and extend the approach, with LG Chem currently leading the way with 74 applications. The examination of the chemistries and binders indicated a growing interest in ASSBs and binder systems without per- and polyfluoroalkyl substances (PFAS), suggesting that both fields demonstrate the greatest innovation potential in conjunction with the successful implementation of the DBE calendaring technologies.

1. Introduction

The global transition towards carbon neutrality is currently unfolding, with secondary energy storage devices playing a pivotal role in terms of facilitating this transition [1,2]. In particular, LIBs have driven this shift, becoming a well-established and mature technology since their commercialisation in the early 1990s [3,4]. However, LIBs still face substantial challenges due to their broadening range of applications, such as in electric vehicles (EVs), which impose increasing demands on cell properties and cost reduction [5–9]. Given that the primary distinction between the costs of LIBs is between the materials and manufacturing, cost reduction is frequently approached from one of these two perspectives [10]. From the manufacturing perspective, electrode production presents one of the most promising innovation

pathways. Its impact on costs and energy consumption is significant, and it involves less intellectual property (IP) protection than cell assembly, thereby offering greater latitude for the protection of innovations [11, 12]. Among the various stages of electrode production, the conventional solvent-based coating, and subsequent drying procedures as well as solvent recovery exhibit the biggest potential for cost reduction. In aggregate, these steps account for approximately up to 50 % of the total energy consumption and up to 20 % of the total manufacturing costs [13,14]. These issues are addressed by the innovative DBE manufacturing, which offers several advantages due to the solvent-free processing [15,16]. The omission of the solvent eliminates both the solvent recovery and the drying step, likely resulting in the greatest savings in terms of energy and costs [17,18]. Further, improvements of the cell performance through the suppression of film delamination and

* Corresponding author.

E-mail address: timgreitemeier@uni-muenster.de (T. Greitemeier).

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preparation of thick and uniform electrodes can be achieved as well [19, 20]. Another potential advantage of dry coating may gain increased attention in the near future with the industrialisation of ASSBs, as the solvent-free processing has been demonstrated to improve compatibility with the production of sulphide-based solid electrolytes [21, 22]. Despite these promising advantages, further development and substantial innovations are required, as none of the existing dry coating technologies have reached a similar technology readiness level (TRL) as the conventional solvent-based coating [23] (Table 1).

The comparatively low TRL of dry coating technologies can be attributed to the broad scope of research and development (R&D) so far, which have tested an extensive range of technologies on a limited scale for a multitude of potential applications. This extensive range of literature known technologies can be ascribed to the following principal mechanisms. The first mechanism comprises the powder application, which is either facilitated by gravity or an electrostatic field, eventually combined with supplementary auxiliary equipment [24, 25]. Another frequently described mechanism is extrusion coating, which permits the processing of higher solid contents in excess of 90 %, although the addition of solvents remains an essential component [26]. Both mechanisms rely on a subsequent calendaring process, which represents another mechanism itself, as the development of funnel-like devices enables the direct application of the powder into the calendar's [27, 28]. An additional mechanism is the single-layer deposition of the active material via physical and chemical vapor deposition [29]. However, industrialisation is hindered by the very low coating speeds that characterise these processes [30]. The aforementioned principal mechanisms were evaluated by Degen et al., which assigned a TRL to all technologies that could be concluded to align with them. This study identified four technologies as the most promising and mature, namely direct calendaring, free-standing electrode fabrication, brush application and electrostatic fluidised bed coating [23]. The preceding two technologies can be attributed to the calendaring mechanism, while the latter two can be assigned to the powder application.

Besides the aforementioned case study, which provided a comprehensive benchmark of the most advanced technologies, prior research has either focused on reviewing the progress and recent developments in

DBE manufacturing [4, 18, 31, 32] or reported a proof-of-concept on a laboratory scale [16, 24, 25, 28, 33, 34]. In contrast to academia, the majority of the knowledge regarding the applications of dry coating exceeding the laboratory scale is found in protected IP, also known as patents. It is acknowledged that some of these patents, such as the innovations by Maxwell regarding free-standing calendaring (Table 3), are well known to experts in the field and form the basis for many further improvements. This highlights the immense value of know-how in this technology area and the necessity to extend it. Nevertheless, the evaluation of the patent landscape in literature regarding dry coating remains insufficient with only two contributions providing a brief overview. In 2022, Li et al. gathered a dataset comprising 256 patents pertaining to binder fibrillation and powder spraying processes, analysing them in terms of temporal evolution and regional distribution. Furthermore, the distribution of chemistries and companies associated with each process was evaluated [32]. A similar approach was implemented in the comprehensive review of Zhang et al., conducted in 2023, which illustrated the annual number of patents filed for LIBs regarding the same processes as in the previous study [31].

In light of the findings of the technology benchmark and the scope and timeframe of both aforementioned studies, a research gap emerges regarding the analysis of the patent landscape of the four most promising technologies in-depth and up to date. Consequently, this work presents a qualitative collection and categorisation of a dataset containing more than twice as many patents as previous studies on the four main dry coating technologies, accompanied by an in-depth analysis. The objective of this study is to provide a comprehensive and up-to-date overview of the key assignees in DBE manufacturing, with a particular focus on bridging the gap between fundamental research and practical applications. In order to address this discrepancy, the analysis employs a quantitative and qualitative approach to investigate the following sub-questions. First, the study analyses the technologies and processes that have been implemented most effectively, as well as those with substantial potential for future innovation. Following this, it delves into an analysis of the leading regions and companies shaping these technologies, examining the scope and nature of their influence across a range of processes. A particular focus is given to determining whether the application of dry coating has already impacted ASSBs. Additionally, the study tracks the evolution of binder systems, detailing their usage trends and mass ratios over time. These insights are intended to aid decision-makers in selecting suitable solutions for future investments and strategy development within this field, in alignment with their specific goals and objectives.

2. Materials and methods

A descriptive patent analysis is employed to assess the technology innovations of DBE manufacturing, utilising the analytical framework illustrated in Fig. 1.

In order to narrow the scope of the analysis to the innovations deemed most significant, the benchmark established by Degen et al. [23] is utilized as a foundation. In their study, different dry coating technologies were subjected to a comprehensive analysis, incorporating both quantitative and qualitative assessment, and evaluated according to their TRLs. The technologies identified as having the highest TRL and overall performance were direct calendaring, free-standing calendaring, brush application and electrostatic fluidised bed coating. In this approach, the latter was extended to incorporate general electrostatic applications, thereby expanding the scope of the analysis. These four technologies are considered to form the basis for further data collection and analysis.

2.1. Data collection and classification

The Derwent Innovations Index (DII) is selected as the appropriate database for the retrieval of the primary dataset, given that it is one of

Table 1
List of abbreviations.

Abbreviation	Definition
ACP	All CPC
ASSB	All-solid-state Battery
CMC	Carboxymethyl Cellulose
CPC	Cooperative Patent Classification
CPI	Combined Patent Impact
CTB	Claims, Title and Abstract
DBE	Dry Battery Electrode
DII	Derwent Innovations Index
EV	Electric Vehicle
IP	Intellectual Property
IPF	International Patent Family
IQR	Interquartile range
LIB	Lithium-ion Battery
OEM	Original equipment manufacturer
PAA	Polyacrylic Acid
PE	Polyethylene
PEO	Polyethylene Oxide
PFAS	Per- and Polyfluoroalkyl Substances
PTFE	Polytetrafluoroethylene
PMMA	Polymethyl Methacrylate
PU	Polyurethane
PVC	Polyvinyl Chloride
PVDF	Polyvinylidene Fluoride
R&D	Research and Development
R2R	Roll-to-roll
RoW	Rest of the World
SBR	Styrene-butadiene Rubber
TRL	Technology Readiness Level
UKRF	University of Kentucky Research Foundation

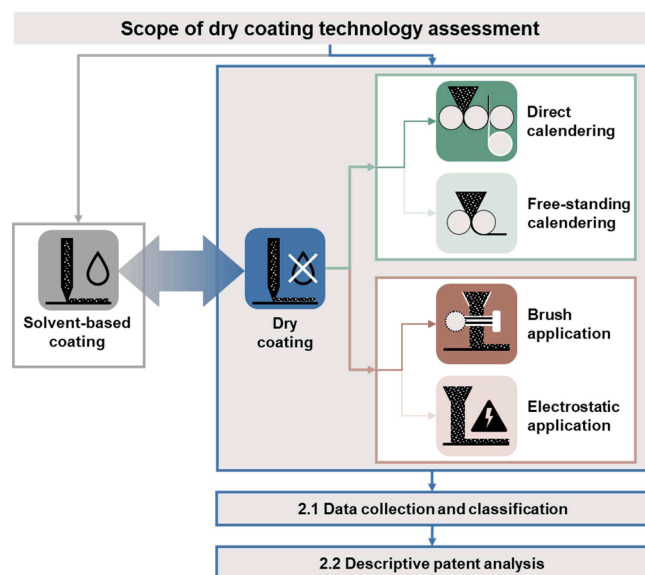


Fig. 1. Analysis framework of the dry coating technology assessment through a descriptive patent analysis.

the most comprehensive and qualitative patent databases encompassing >80 million patent documents from 59 global patent-issuing authorities e.g., Espacenet (Supplementary Table 1). The implementation of International Patent Families (IPFs) facilitates the organisation of all patents pertaining to a single invention into a single IPF, thereby eliminating redundancies and enhancing the precision of the dataset [35]. In addition, DII provides standardized abstracts, citation information, and harmonized assignee data, which collectively ensure that it is sufficiently comprehensive for scientific and strategic analyses. We achieve the broadest possible scope by basing the initial search query on Cooperative Patent Classification (CPC) codes. In accordance with the CPC scheme, which is used to hierarchically categorise patents in relation to the technological fields of the invention, the CPC code *H01M* and all subsequent codes are employed for the collection of all innovations pertaining to processes and means for the direct conversion of chemical energy into electrical energy. The resulting primary dataset comprises 471,520 IPFs, which constitute the basis for all subsequent analytical procedures. In the following, a combination of CPC code search and keyword search in titles, abstracts and claims is employed to narrow the datasets towards the relevant coating patents (Table 2). Moreover, the analysis is constrained to the period between 2004 and 2024, as the initial significant advancements in DBE from Maxwell were documented

Table 2

Patent data search queries and total patent counts of collected datasets. (ACP: All CPC, CTB: Claims, Title and Abstract).

Dataset	Tier	Search query	Count of patents
Primary	1	ACP = (H01M)	471520
Solvent-based coating [2004–2024]	1A	CTB = ("wet" AND "coat")	5301
Dry coating [2004–2024]	1B1	ACP = (H01M00040402)	693
	1B2	Literature [32]	
	1B3	CTB = ("fiberization" OR "fibrillation")	
	1B4	CTB = ("dry electrode")	
	1B5	CTB = ("dry film")	
	1B6	CTB = ("solvent free" OR "solventfree" OR "solvent less" OR "solventless")	
	1B7	CTB = ("fluidized bed")	
	1B8	CTB = ("brush" AND "powd")	
	1B9	CTB = (("freestand" OR "selfstand" OR "selfsupport") AND "dry")	

in 2004, and the number of IPFs from preceding years is negligible. The aforementioned analytical procedures are performed by importing the primary dataset into the *Python 3.10* software environment, which enables the search queries to be specified by employing Boolean search operators (AND, OR, NOT). The search query regarding the solvent-based coating is based exclusively on keywords, despite the potential limitations regarding the scope and reliability of the resulting data. These limitations are largely mitigated, as the variation of the keywords and the implementation of CPC codes solely alter the total number of IPFs, while the prevailing trends and key narratives remain unchanged. As the key objective of the analysis is to assess the DBE manufacturing, a series of search queries are conducted on the primary dataset in order to identify all pertinent IPFs. Each dataset (1B1 to 1B9) is qualitatively analysed in order to extract the patents corresponding to one of the four technologies, devices, and materials, only including inventions which are completely solvent-free. In step 1B2, the patents identified in the preceding analysis by Li et al. are cross-referenced with our dataset, and any missing patents are included and classified in accordance with this approach [32]. The in-depth analysis of each dataset is essential due to the fact that straightforward keyword searches yield a considerable number of irrelevant IPFs. Furthermore, the current CPC scheme is deficient in terms of providing suitable dry coating codes. The issue of redundancy in the patents included in the datasets is addressed by implementing a consistent verification process. This entails cross-referencing the application numbers of previously revised patents with those of the newly gathered patents, ensuring that already considered patents are not included in subsequent datasets. The qualitative revision of each patent is designed to ensure the thoroughness and legitimacy of the resulting 693 IPFs, which are contingent upon the author's level of expertise and knowledge. The final dataset (Supplementary Table 2) contains more than twice as much IPFs than those reported in previous studies [31,32], with the further categorisation facilitating in-depth analysis.

2.2. Descriptive patent analysis

It is crucial to consider that due to the 18-month publishing period for patents and additional delays resulting from regionally distinct publishing procedures, the years 2023 and 2024 may be devoid of a number of currently unpublished IPFs. Nevertheless, both years are included to provide a comprehensive and up-to-date overview of the dry coating patent landscape. The four technologies – direct calendering, free-standing calendering, brush application, and electrostatic application – are expanded by the categories device and material to incorporate all patents belonging to DBE manufacturing that do not describe one of the specific technologies. The respective categories are assigned to a patent exclusively in instances where they are explicitly mentioned in the patent text. Technologies are prioritized to devices and materials. Direct calendering constitutes the sole exception, as all patents pertaining to calendering technologies are assigned which do not explicitly address the fabrication of a free-standing electrode. In addition, each technology patent is allocated to a specific process, which is selected through an evaluation of the dataset. As a result, six main processes are identified, namely binder fibrillation, roll-to-roll (R2R), fluidised bed, spraying, brush and hot pressing. The R2R process employs the same fundamental principles as binder fibrillation, with the exception that the formation of the fibrils is not explicitly described in the patents.

In the next step, the dataset is broken down into the most prominent regions and the constituent assignees, both founded upon the column 'Ultimate Parent'. From a regional perspective, the largest patent portfolios are held by China, Germany, Japan, South Korea, and the United States, with the remainder of patents being allocated to the rest of the world (RoW). Given the considerable number of assignees operating within this field, only those that have published a minimum of 20 patents are included in the subsequent analysis, resulting in a total of six assignees. In addition, each patent is categorised as either ASSB, LIB or

'Miscellaneous' in accordance with the target chemistry of the invention. If a patent refers to multiple chemistries, the most highly rated chemistry is assigned. The rating is determined by the author, with the highest ranking given to ASSB, followed by LIB, and concluding with 'Miscellaneous'. For illustrative purposes, we direct to examine the patents with publication numbers *CN111004404B* and *US20230411588A1*. The former patent describes an application in ASSB and fuel cells, while the latter patent describes a free-standing calendaring method, as well as the required apparatus (Supplementary Table 4).

The quality of each patent is addressed by the 'Combined Patent Impact' (CPI), a predictive analytic metric implemented by the DII. This metric considers two factors: the influence of a patent in its respective domain and its importance to the assignees. The lowest possible value for the CPI is 1; as this value increases, so too does its impact. This approach is further extended by the analysis of the current status of each IPF in the column 'Family status', which divides the patents into the sections granted, pending, expired, abandoned, and withdrawn. The data is then utilised to calculate a median CPI and a 'Granted-to-X ratio' (Supplementary Table 5) for the patent portfolios of each technology, region, major assignee, and chemistry. The ratio indicates a strong active portfolio if the value exceeds 1. Further, all assignees were categorized by their respective type, including original equipment manufacturers (OEMs), cell producers, equipment suppliers, and research institutes. We then analysed the assignee types regarding the key metrics in this study (Supplementary Table 6).

The final part of the descriptive patent analysis addresses the respective binder systems utilized in the patents. Consequently, the whole patent documents are screened regarding the selected binder systems and the corresponding weight ratios, incorporating each variation which is successfully implemented in the invention. As a result, a single invention may yield a multitude of potential binder systems. In instances where a range of weight ratios was specified, the mean value was calculated to convert it into a single value. As this broad range results in elevated mean values and considerable standard deviations, the absolute values in this analysis are of limited significance, thus placing the emphasis on developments and subsequent trends. The clarity and concision of this approach is achieved through the restriction of the range of binder systems to the most commonly used. These include polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), combinations of PTFE with other binder systems (PTFE + X), and binder systems that are completely PFAS-free.

3. Results and discussion

As the DBE manufacturing represents a novel approach to the conventional solvent-based coating, both techniques are in direct competition with regard to their future role and market share in the production of battery electrodes. It is therefore of interest to examine the evolution of the patent numbers associated with each technology in comparison. Fig. 2 illustrates the total and the annual number of patents for both solvent-based and dry coating. While the dataset regarding the solvent-based coating accumulates a total of 5301 patents from 2004 to 2024, the number of patents assigned to dry coating is significantly lower, with a total of 693 patents. It is crucial to acknowledge that the number of the latter has the potential to expand if the scope is extended to include additional technologies and databases. In the context of the extensive range of results yielded by the variation of search queries, it is reasonable to conclude that the influence of these other technologies can be disregarded in comparison to those that are the subject of this study. Given the considerable disparity in the TRLs between the two technologies, a direct comparison on an annual basis is insufficient. Instead, it is more revealing to search for historic trends in solvent-based coating in order to gain insight into the potential trajectory of dry coating.

The historical perspective reveals 2009 as the start of exponential growth in patenting and subsequent expansion of solvent-based coating.

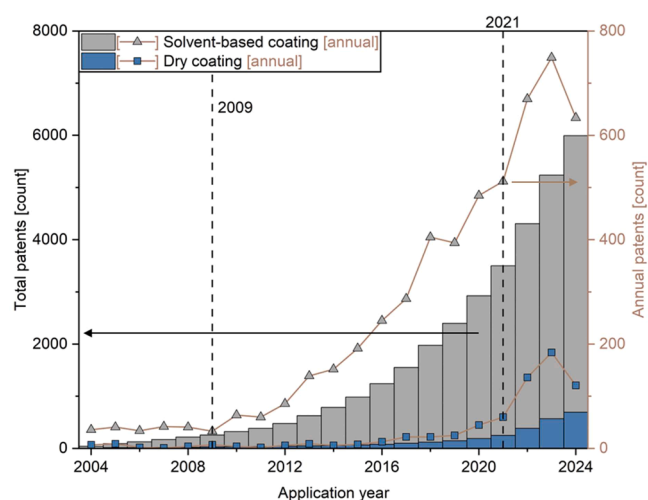


Fig. 2. Comparison of the total (left) and annual (right) count of patents between solvent-based and dry coating.

This inaugural point of patenting is consistent with the second phase of innovation regarding the conventional gigafactory cell production processes and the simultaneous launch of sales of LIBs for EVs [36]. Up until 2009, the total number of patents reaches 227, with 33 IPFs being published in the same year. In comparison to the dry coating dataset, the numbers are similar to those observed in 2021, when the total number reaches 252 patents. However, it should be noted that 60 patents are solely published in this year. This probably derives from the fact that the advancement of dry coating benefits from the existing expertise in solvent-based coating, thereby accelerating innovation [37,38]. It can thus be suggested that the year 2021 marks the advent of dry coating, with subsequent upscaling of this technology occurring in a manner similar to that observed with solvent-based coating 12 years prior. Therefore, the analysis of the current state of the patent landscape and, consequently, the technology is pivotal to derive implications and forecast potential developments in the upcoming years.

3.1. Dry coating innovations

The first analysis step involves an investigation concerning the a) historic evolution of each DBE technology, devices, and materials and the b) distribution of the principal processes employed for these technologies (Fig. 3).

A review of the historical development reveals a notable increase in the number of patents related to free-standing calendaring in the years 2004 and 2005. This growth in patent activity illustrates the foundation upon further innovation of this technology is built. In the ensuing years up to and including 2015, no discernible trend emerges. Since then, the annual tally of patents for direct and free-standing calendaring has risen, reaching a maximum of 69 and 60 patent filings in 2023. This leads to both innovations being the most dominant and successfully implemented technologies, with 224 and 244 total patents. The number of patents associated with electrostatic applications exhibits a comparatively lower growth rate, reaching a total of 57 patents. In contrast, there is no apparent growth trajectory for brush applications, resulting in a total of only 18 patents. Evidently, the absence of IP protection allows a certain amount of latitude for radical innovation, however this is no indication of the economic success to be expected in this area. As it seems significantly harder to attain a competitive advantage in direct and free-standing calendaring through IP protection, it may be advisable for smaller companies to pursue collaborative endeavours, such as Maxwell and Tesla [39], rather than investing in in-house R&D departments. In addition to the DBE technologies, further patent filings encompass innovations pertaining to devices and materials. The latter

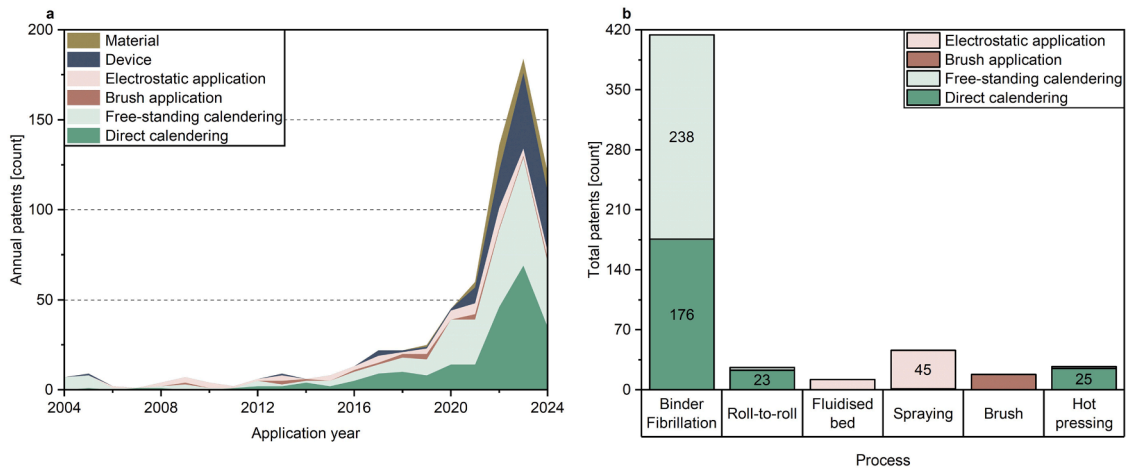


Fig. 3. Patent counts of DBE technologies, devices, and materials: a) Annual trends and b) total patent counts by process. Sample size is $N = 693$.

particularly comprises the development and preparation of modified binder systems, indicating the importance of the binder choice on the processability of DBE manufacturing. A detailed investigation of the device patents further strengthened the crucial role of calendering technologies, as the majority of the 113 patents covers calendar or powder supply systems.

Out of the six processes depicted in Fig. 3b, binder fibrillation is the primary process in both direct and free-standing calendering (414 total patents). All remaining processes are notably inferior in terms of patent count, with R2R and hot pressing being employed for the calendering technologies as well. Interestingly, the electrostatic application approach can be subdivided into two discrete processes: namely, fluidised bed and electrostatic spraying, which are distributed with 12 and 45 patents, respectively. The results indicate that binder fibrillation is the most promising process for achieving direct impact on the industry through a substantial innovation. Nevertheless, given the significant expertise in the field of binder fibrillation, it is considerably more challenging to identify a significant innovation than it is for other processes. In combination with the previous results of electrostatic and brush applications being promising technologies for IP protection and R&D development, the processes fluidised bed, electrostatic spraying and brushing are identified as more concrete targets. The most influential patents based on the highest CPI in each subcategory included in Table 3, providing insights about their current status, assignees and implemented binder systems. The patent family size and count of forward citations further indicate the ongoing influence of these central innovations.

3.2. Regional breakdown

In this section, the dry coating patent landscape will be examined regarding the regional expertise. Accordingly, Fig. 4 shows the a) historic patenting of the five most promising regions and b) categorises their respective portfolios in accordance with the four major DBE technologies, devices, and materials. It becomes apparent that the patenting peak in the early 2000s is initiated by the United States, which thus became the pioneers of free-standing calendering. Up until 2020, the United States held the biggest portfolio but fell to third place with 109 total patents after China (311) accelerated its activity in 2020, followed by South Korea (133) in 2021. From a European standpoint, Germany continues to be the most enigmatic competitor, having accumulated a total of 81 patents. In contrast, Japan (34) witnessed a substantial decline in its efforts, a trend consistent with that observed in other technologies [12].

The patent portfolios of each region are provided in Fig. 4b, showing that China has the most extensive portfolio in each technology, with the exception of free-standing calendering. This diversification is also resembled by the other regions as none of them is exclusively focused on a single technology. In contrast to China, where direct calendering is a particular focus, the portfolios of South Korea and the United States are characterised by a greater emphasis on free-standing calendering. This emphasis has resulted in the United States occupying the leading position in this technology, partly deriving from its pioneering role at the beginning of the century. Germany currently is the frontrunner in device patents with a particular focus on calendering technologies, whereas

Table 3

Most influential patents with the highest CPI in each subcategory. (CMC: Carboxymethyl Cellulose, PAA: Polyacrylic Acid, PE: Polyethylene, PEO: Polyethylene Oxide, PMMA: Polymethyl Methacrylate, PVC: Polyvinyl Chloride, SBR: Styrene-butadiene Rubber, UKRF: University of Kentucky Research Foundation).

Category	Subcategory	Publ. Number	Year	Status	Assignee	CPI	Family size	Forward Citations	Binder (wt %)
Direct cal.	Binder fib.	US20110165318A9	2005	Abandoned	Tesla	13.8	1	41	PTFE (3 to 8)
	R2R	CN110828772B	2019	Granted	LinkData	5.04	1	7	N/A
	Hot pressing	CN112542563B	2020	Granted	EVE Energy	6.39	1	10	PVDF (3), CMC (1.5), PAA (5)
Free-standing cal.	Binder fib.	US20130157141A1	2012	Abandoned	Tesla	77.1	1	58	PTFE (3 to 15)
	R2R	US20140030590A1	2012	Pending	Global Graphene Group	76.43	1	136	PTFE (10), PVDF/CMC/SBR/PVC/PE (N/A)
	Hot pressing	DE102017217656A1	2017	Pending	Bosch	2.68	3	1	CMC (N/A)
Brush app.	Spraying	US20190036103A1	2017	Granted	Honda	10.77	7	26	Binder free (0)
	Brush	US20110135836A1	2009	Expired	XACTIV	8.74	1	19	PTFE (N/A)
	Fluid. Bed	CN102176389B	2010	Granted	GMCC	3.69	1	8	PMMA (7)
Electrostatic app.	Spraying	US20170098818A1	2016	Abandoned	UKRF	13.46	1	21	PVDF (5)
Device	Device	US11239454B2	2017	Granted	Tesla	7.06	11	12	PTFE (N/A)
Material	Binder	US11545667B2	2019	Granted	Tesla	5.04	7	12	modified PTFE (N/A)

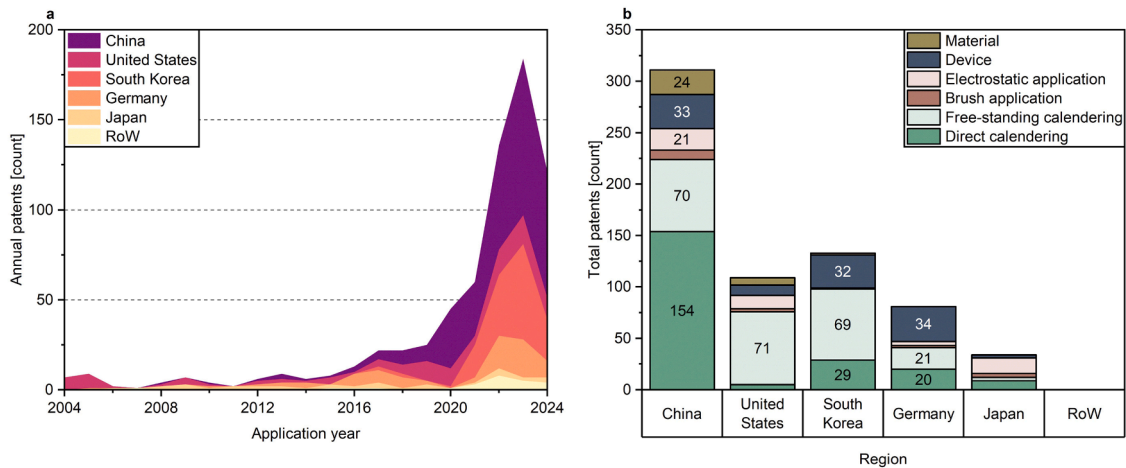


Fig. 4. Patent counts across the five most promising regions **a)** on an annual basis as well as the **b)** total regional count distinguished by DBE technologies, devices, and materials (RoW includes the rest of Europe). Sample size is $N = 693$.

Japan's portfolio exhibits a balanced allocation of direct calendering and electrostatic application technologies. In comparison to the findings of our preceding study into the IP landscape of the LIB value chain in gigafactories [12], the aggregate proportion of patents held by China is marginally lower at 45 %. It is noteworthy that Japan's 32 % share does not correspond to its position in the dry coating landscape, where it has a reduced share of 5 %. This gives rise to a heightened level of competition for the remaining regions, with their respective shares in dry coating being more than twice as high. From a qualitative perspective, the United States are distinguished by a median CPI of 9.11 (Supplementary Table 1) across the entire portfolio, which is approximately three times higher than the CPIs of the other regions. This underscores the pivotal role of the United States as a leading innovator in DBE manufacturing. This assertion is further substantiated by a Granted-to-X ratio of 1.02, which indicates that the majority of its patents are granted and still alive (Supplementary Table 1).

3.3. Assignee breakdown

After investigating the regional expertise distribution, the major assignees possessing the biggest portfolio are analysed. Fig. 5 shows the patent distribution of the six leading assignees on an **a)** annual basis and **b)** their respective DBE technologies, devices, and materials.

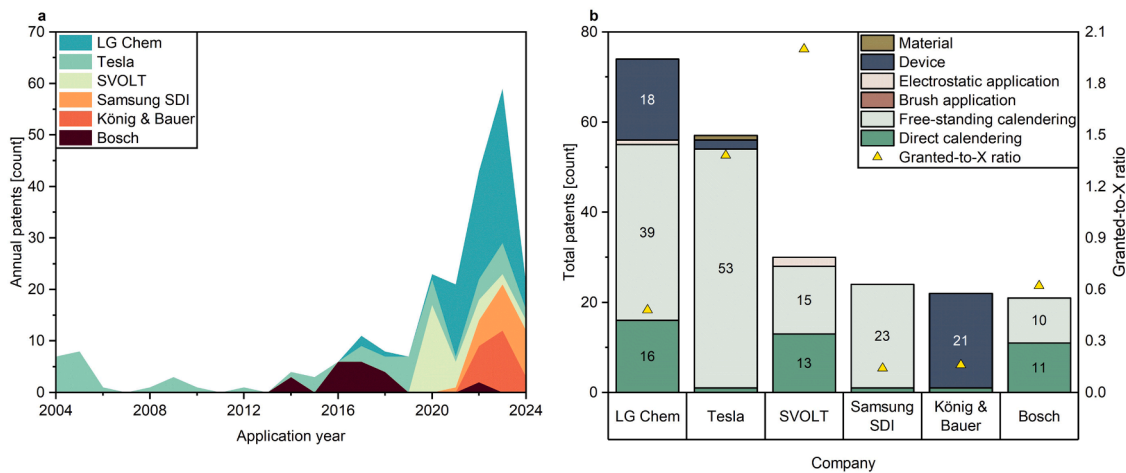


Fig. 5. Patent counts of the six leading assignees **a)** on an annual basis as well as the **b)** total count of patents distinguished by DBE technologies, devices, and materials and Granted-to-X ratio (Indicator of the actual portfolio strength; calculated by dividing the number of patents granted by the sum of patents pending, expired, abandoned, or withdrawn). Sample size in both graphs is $N = 228$.

evident in the case of Bosch and SVOLT, the latter of which is the sole Chinese enterprise to have secured 20 or more patents. The lack of Chinese assignees is in contrast to the dominance of China as a region in this technology as well as industry. One explanation could be the vast number of assignees, that spread their expertise, resulting in a high number of Chinese assignees with more narrow portfolios [41]. In contrast to the prevailing trend of upward mobility in the majority of patent applications, Bosch opted to cease patenting in 2019. In a manner consistent with the broader pattern, they initiated their endeavours by filing patents in 2014 and the subsequent years. However, they appear to have withdrawn from the competition and terminated their R&D activities in this technology. This tendency is exemplified by the relatively low Granted-to-X ratio of 0.62, despite the majority of filings dating back more than five years. SVOLT, in contrast, represents a fully committed innovator with an above-average median CPI of 4.02 combined with a Granted-to-X ratio of 2.00, meaning that two-thirds of the portfolio is currently granted and alive, despite having started filing in 2020.

Samsung SDI and König & Bauer have recently joined the top six, commencing their patenting activities in 2021 and 2022, respectively. While Samsung SDI has opted for a free-standing calendaring approach, König & Bauer is noteworthy for its expertise in DBE manufacturing devices. Each patent under consideration represents a distinct innovation in device design, specifically for calendars and corresponding powder feeders intended for industrial use. The client responsible for this initiative and, consequently, the cooperating partner is PowerCo, a subsidiary of Volkswagen. In 2023, the two companies entered into an agreement for the joint development of dry coating technology, thereby demonstrating PowerCo's commitment to advancing the DBE manufacturing [42]. In light of the recent nature of their endeavours, four of the six foremost companies exhibit a Granted-to-X ratio below 1, with the incumbent leader in terms of quantity, LG Chem, demonstrating a ratio of 0.48 (Fig. 5). This finding indicates that the expertise required for DBE manufacturing is predominantly retained by Tesla, exhibiting both substantial quantity and quality.

As reflected by the major assignees, DBE manufacturing garners the interest of a diverse range of assignee types. The analysis of the key metrics (Supplementary Table 6) reveals that cell producers resemble the biggest type of assignees with 266 total patents, especially focussing on dry calendaring technologies. Concurrently, equipment suppliers (175 total patents) are the most dominant assignee type in device and material patents, aligning with their role as suppliers for cell producers and OEMs in the supply chain. While OEMs (177 total patents) do not lead in a specific technology in terms of quantity, they possess the highest median as well as mean CPI of all assignee types and show the

highest Granted-to-X ratio, resembling their high impact and financial power throughout the value chain. Research institutes, with a total of 75 patents, demonstrated a comparatively low level of patenting activity. Germany emerged as a significant contender, ranking second only to China in terms of patenting activity, a reflection of its pivotal role in this technological domain.

3.4. Chemistry breakdown

On the way to its own industrialisation, DBE manufacturing has the potential to facilitate the industrialisation of ASSBs, which is currently hindered by, i.e. solvent sensitivity and fragility, occurring in conventional solvent-based coating [17]. Consequently, an analysis is conducted on the dry coating dataset with regard to the chemistries that were applied in the patents. In Fig. 6, the patent count of the selected chemistries is presented on two different scales: first, on an annual basis with regard to their filing status, and second, on an aggregate basis, considering the total of the six leading assignees.

The peak in patenting activity in the early 2000s, which can be attributed to the R&D conducted by Maxwell, falls within the category of 'Miscellaneous', supercaps in particular. This period of heightened patent activity has been followed by a paucity of development until 2023. Since then, 17 patents have been filed in the last two years, which are mainly related to the increasingly discussed sodium-ion batteries (SIBs), and have not yet been granted [43]. The number of patents filed is notably lower than that observed in LIBs, which has experienced a substantial rise in activity since 2014, reaching a peak of 100 annual patents in 2023, of which 77 are still pending. Similarly, interest in ASSBs emerged in the same year, albeit at a relatively modest level, with a maximum of 25 patents recorded in 2023, and only four of them were granted. Nevertheless, the increased patent filings regarding ASSBs in recent years, suggest a growing interest in this field. In order to gain further insight into the chemistry trends, it is essential to examine the activities of the leading assignees, as they are often the primary drivers of technological innovation due to their substantial R&D investments. The portfolios of the majority of the industry's foremost assignees reflect the general trajectory of chemical developments within this technology, most of them having a particular emphasis on LIBs. It is notable that Tesla is the only assignee within this group that have a significant number of patents in the category designated as 'Miscellaneous'. This number corresponds well to Maxwell's pioneering role in the implementation of free-standing calendaring for supercaps in the early 21st century. Interestingly, despite the device manufacturer König & Bauer, each assignee has at least one patent regarding ASSBs, which underlines the growing significance of this chemistry even further. In particular,

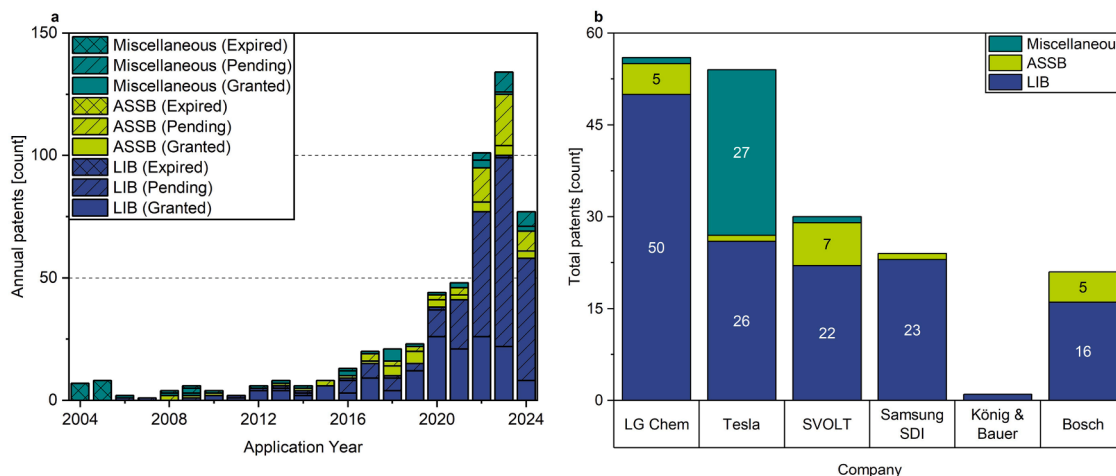


Fig. 6. Patent counts of the chemistries **a)** on an annual basis regarding their filing status (Sample size: $N = 534$) and **b)** the total of the six leading assignees (Sample size: $N = 186$).

SVOLT and the Hyundai Motor Group have emerged as the leading companies regarding this chemistry, with a total of seven patents each (Supplementary Table 2).

3.5. Binder systems

The preceding analysis of the technologies has demonstrated that direct and free-standing calendaring represent the most prevalent DBE manufacturing technologies to date. It is thus pertinent that this study adopts a more detailed examination of these technologies, with a focus on their constituent components. One component which has been the focus of particular attention is the binder, given that the systems currently in use may no longer be viable in the event of a PFAS ban [44, 45]. In order to track recent trends and identify new approaches, the binder mass ratios of the most commonly used binder systems are analysed from a historical perspective (Fig. 7). The results show that the preferred binder is PTFE, especially in binder fibrillation, which has been consistently utilised in patent applications since 2004. The median mass ratios have diminished by over 50 % over the past two decades, with this trend showing an accelerated trajectory since 2019. This overall trend aligns with current research reaching PTFE binder contents

below 2 wt % [46–48]. Furthermore, the consistent decrease in the interquartile range (IQR), which signifies the spread of the central 50 % of the data, suggests a convergence and a reduction in variability among the various patent approaches. This trend is particularly noteworthy as it coincides with an increasing sample size, exceeding 100 in 2023, suggesting that the observed convergence reflects a genuine stabilization of the underlying distribution rather than a statistical artifact. The primary cathode binder in solvent-based coating, PVDF, is also investigated as an alternative since 2014, particularly in the context of hot pressing, where the binder is subjected to high temperatures and becomes molten [49]. However, the sample size remains constrained to a maximum of 10 patents per year, a limitation that is also observed in other binder systems (see Fig. 7b and d), thereby underscoring their current negligible role. Since 2015 the focus of the patents shifts towards both, binder systems with combinations of conventional binders and PTFE as well as PFAS-free alternatives. The latter are predominantly represented by PE, PAA, and polyurethane (PU), which have been primarily developed as substitutes for the binder fibrillation process. Due to the prevailing uncertainty surrounding the regulation of PFAS, it is anticipated that the search for viable alternatives will intensify the R&D efforts in the coming years [44,45].

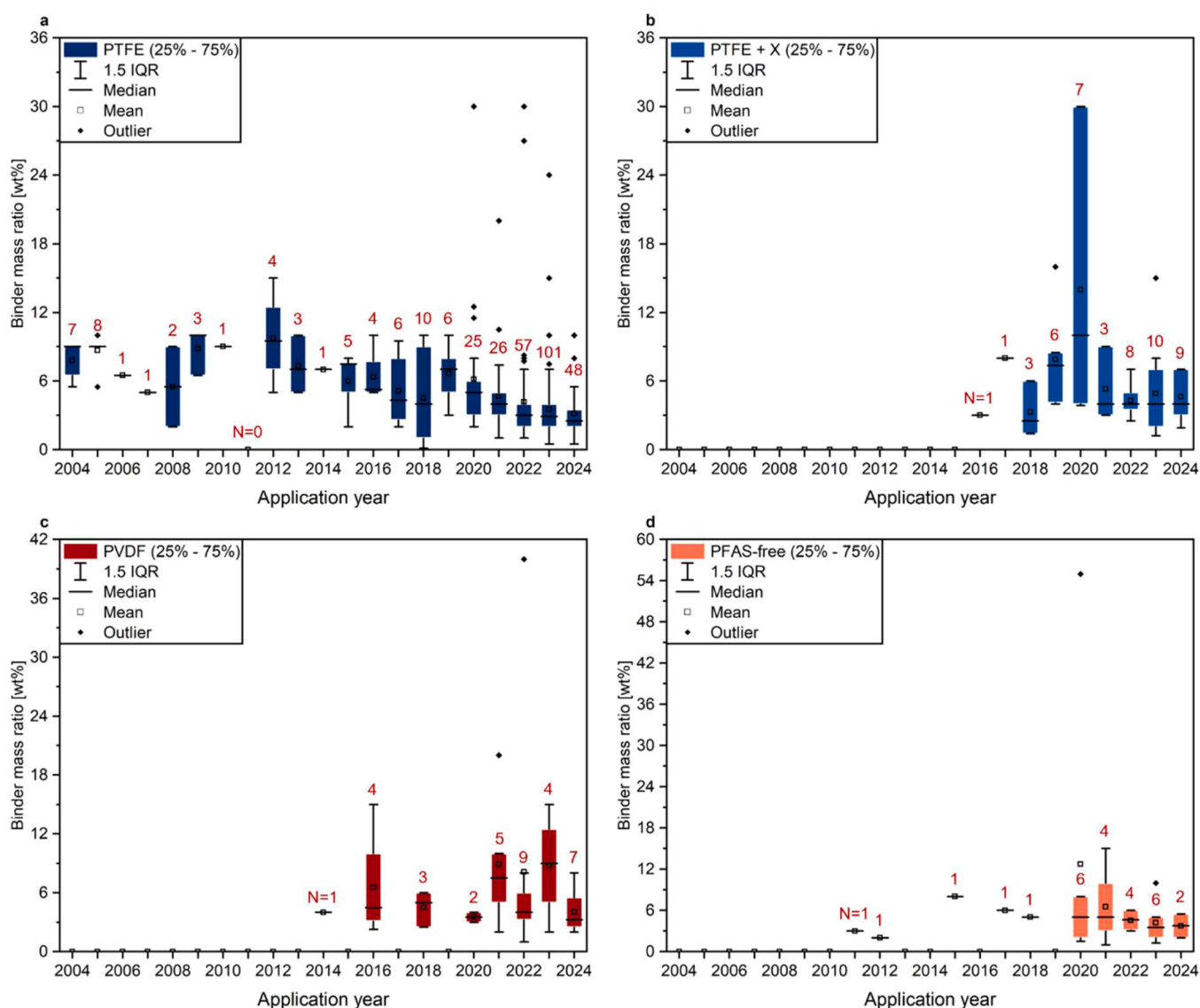


Fig. 7. Development of the median, mean binder mass ratios, IQRs, 1.5 IQRs and outliers (in weight percent (wt %)) of a) PTFE, b) PTFE+X, c) PVDF, and d) PFAS-free used in dry calendaring technologies (N: sample size per year).

4. Conclusion

The analysis of patents through a variety of data science methods has already demonstrated its value as a tool for monitoring trends in emerging industries and technologies, with this study presenting an in-depth analysis of the DBE patent landscape. By comprehensively analysing the four prevalent technologies, this work offers a current overview of the leading regions and assignees in the respective technology areas. A detailed examination of this data facilitates the identification of trends and strategic insights, bridging the gap between academic research and industrial expertise.

Firstly, free-standing calendering is identified as the currently most dominant technology in terms of total patent numbers. The principal process underlying this technology is identified as binder fibrillation, which is also extensively employed in direct calendering. Both powder application techniques – brush and electrostatic – are deficient in terms of IP protection, thereby presenting a potential opportunity for innovation. From the regional perspective, China accounts for the majority of patents across all DBE technologies, with the exception of free-standing calendering, where the United States demonstrate a slight advantage. Despite the lead of China in other parts of the LIB value chain, the gap to the competitors in DBE is relatively small [36]. South Korea is identified as a region warranting further investigation, given the notable surge in annual patenting observed in recent years. In total, the foremost regions direct their attention towards a comprehensive diversification of technological specialisation, thereby cultivating a global repository of expertise. In addition to the regions, six assignees have been identified with patent portfolios exceeding 20 patents, with a particular focus on calendering mechanisms. Currently, the largest portfolio is held by LG Chem, with Tesla, who are identified as pioneers in the field of free-standing calendering in the early 2000s, as the closest competitor. The late market entry of four out of the six leading companies, namely LG Chem, SVOLT, Samsung SDI, and König & Bauer, over the past four years suggests that there has been a considerable increase in the prominence of DBE manufacturing, with the increased efforts probably continuing in the near future.

Furthermore, the analysis of the chemistries illustrates that LIBs are the dominating, with ASSBs gaining increased attention recently. The latter is primarily approached by SVOLT and the Hyundai Motor Group, both accumulating seven patent filings each. Finally, the investigation of binder systems has demonstrated that PTFE is the most commonly used binder, with average mass ratios having been reduced by over 50 % over the past two decades. The endeavours to implement alternative binder systems have intensified since 2018, including the introduction of completely PFAS-free binders e.g., PE and PAA [50,51].

Based on these insights, decision makers are better positioned to identify the most promising technologies, regions, and assignees for investment and collaboration, in alignment with their individual objectives. If the respective goal is to leverage or set up internal R&D activities to protect IP and thereby gain a competitive edge, powder applications could present a promising avenue for innovation. In contrast, the existing and rapidly increasing knowledge base in the field of calendering mechanisms, which is extensively protected by patents, could be utilised by forming cooperative relationships with the leading regions and assignees that possess this expertise. Nevertheless, the application of DBE manufacturing on ASSBs, as well as the development of alternative binder systems offer the biggest potential for R&D investments and could have a crucial impact on the market, particularly in terms of IP protection.

The insights offered by this study are nonetheless constrained by certain limitations, including a restricted scope of data acquisition that may result in the exclusion of relevant patents. The restriction is attributable to the exclusive reliance on the DII as the sole database and the deployment of keywords and CPC codes. The latter has already been addressed via the qualitative assessment of multiple iterations throughout the analysis, thereby extending the scope to a near

maximum. However, further iterations and the implementation of additional databases and sources could enhance the comprehensiveness of the analysis.

Future work could implement industry interviews and supplementary data sources to enhance and further validate the results. As the patent landscape in this rapidly increasing technology continues to expand, it would be worthwhile to conduct this approach on a regular basis, approximately every few years, in order to gain insight into the trajectory of each trend. One significant trend that may emerge is the increased patenting of entirely novel and modified binder systems. This hypothesis is indicated by the findings of this study, and it is plausible that this trend will be exacerbated by regulatory changes, such as the PFAS ban that is currently under discussion. Additionally, an analysis of other innovations in the manufacturing of LIBs, i.e. innovations in electrode manufacturing such as laser drying [52,53], could prove beneficial. In such instances, open innovation has the potential to fulfil an instrumental function by facilitating the acceleration of the implementation of said processes on an industrial scale. By directly comparing the patent strategies, insights could be gained into the general innovation behaviour in the context of the cell manufacturing.

CRedit authorship contribution statement

Tim Greitemeier: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Simon Lux:** Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.nexres.2025.101118](https://doi.org/10.1016/j.nexres.2025.101118).

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