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Modeling Large-Scale Manufacturing of Lithium-Ion Battery Cells: Impact of New Technologies on Production Economics

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***Abstract*—The global demand for electric vehicles is increasing exponentially, as is the demand for lithium-ion battery cells. This has led to a strong ongoing competition among companies to achieve the lowest battery cell production cost. Herein, to provide guidance on the identification of the best starting points to reduce production costs, a bottom-up cost calculation technique, process-based cost modeling (PBCM), for battery cell production is reproduced and validated by drawing on a consistent dataset of a real battery cell production plant. The model is based on teardowns of a real battery cell factory and will prove useful for planning activities of today's, so-called, "giga factories." The PBCM performed in the present study involves discussions on, e.g., production balancing, relocation of factories to low-wage countries, usage of new production and cell technologies, etc. The use of novel approaches, such as tabless cell design, dry coating, and NMC811 chemistry, is discussed. Finally, the ways in which battery cell production costs can be reduced further in the forthcoming years are shown, and implications for researchers, practitioners, and policy makers are provided.**

***Index Terms*—Battery cell, cost optimization, process-based cost modeling (PBCM), production costs.**

I. Introduction

THE worldwide demand for battery cells is increasing exponentially, driven particularly by the growing success of electric vehicles (EVs). Current studies predict a demand of approximately 2600 GWh/a for 2030 [1]. Others even predict demands of up to 10 000 GWh/a, but without referencing to an exact year [2]. As a result, battery cell production capacity is being rapidly expanded worldwide; e.g., by the end of 2020, 800 GWh of battery cell production capacity was announced or planned in Europe alone [3]. A change in this trend is not expected at present. Such a scenario has led to a strong ongoing price competition among battery manufacturers. The literature reports on different effects that contribute to the cost reduction of battery technology. For example, it has been reported that economies of scale—cost reduction through learning rate after increasing production quantity (in this case doubling)—can reduce the price as much as 6%–9% per battery pack [4]. The development of optimized materials for use in lithium-ion cells, such as active materials for cathodes, anodes, and electrolytes, as well as corresponding inactive materials, can help achieve higher energy densities and lifetimes, thereby indirectly reducing costs at the cell level since less material is required per cell [5]. In addition, price advantages in terms of more efficient methods of material synthesis can be passed on to cell-producing customers. Another crucial cost-reducing factor is the optimization of the battery cell production process. Studies have reported high cost sensitivity of electrode production, advanced formation and aging processes, continuous process control, and process substitution as targets for innovative process technologies [6]. The integration of new production technologies is required to reduce prices even further [2]. However, for many production researchers and manufacturing engineers, it is rather difficult to identify the part of the process chain for which new production technologies are needed the most and the economic impact these new approaches might bring. One major reason is that the battery cell cost and, in particular, the exact cost structure is somewhat complex and involves variables other than those from usual cell and process design activities. The general obstacles that inhibit production of reliable battery cells that are cost efficient are as follows.

1) Costs usually depend on industry activity and are, therefore, strongly **confidential**.
2) The battery market is not fully developed yet. Battery cells, especially for EVs, are being produced in significant amounts only for the last couple of years. Thus, the current **knowledge and experience** base for EV applications is still inadequate.
3) As the market is relatively young and growing strongly, production **know-how** is being learned **continuously**, leading to a decrease in production **costs**.
4) There is no stable ratio between **supply and demand**. Both are changing rapidly and have a substantial impact on costs and prices. Other influencing factors include market structures such as possible oligopolies and lack of information availability, the discovery of new raw material sources and development of efficient refining methods,

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and the use of new cell chemistries (which changes the demand for existing materials and thus costs). Note that the terms "price" and "cost" are often used simultaneously in existing studies.
5) Battery cell costs **depend** strongly on material prices, and which in turn depend significantly on the **quantity of purchase**, which varies as well.

As every business-oriented organization aims to maximize profit while reducing costs under the given conditions, the same is true for battery cell production. A literature analysis by Duffner et al. [7] from 2020 shows an average cost decrease of approximately 50% for lithium-ion battery cells between 2015 and 2020. More importantly, even today, the cost assumptions range from 84 [8] to 138 €/kWh [3] for state-of-the-art lithium-ion NMC cell chemistry. Thus, there is a large variation in reported costs, in general and over time. In addition, many costs for battery cells are not split in terms of material and production costs. There are studies that try to analyze the **cost structure**, but strong differences can be observed here as well. The German Engineering Association (VDMA) reports, for example, material cost proportions of 60% [3], while BMW has reported material cost proportions of 80% [9]. Therefore, there are large differences in **quotable battery cell production costs,** and it is difficult to elaborate on their validity and how they are calculated. Similarly, there are papers and publications that explain the breakup of production costs through different methodological approaches (e.g.,[3], [7], [10], [11], [12], [13]). Most of these studies gathered information from various other sources (secondary data). However, the combination of these data from different sources for a cost model is not perfect because of the following.

1) The primary source and its credibility are mostly unknown.
2) The locations of the analyzed production sites differ, which has a significant effect on production costs.
3) The exact time of data collection is unknown. Owing to the rapid developments in battery cell production, the life of available information diminishes fast.
4) The exact cell chemistry is unknown or not named, even though it has a significant effect on cost per kWh.
5) The cell format is unknown, which also has a significant effect on the cost per kWh.
6) The cell design is unknown. If a cell design has a high-power layout or a high-energy layout, it also has a significant effect on the cost per kWh.

Despite the abovementioned shortcomings, a cost model involving real production-related large-scale data on state-of-the-art battery production technology, allowing for full transparency and access to primary data, is missing. In addition, the effects of new battery cell manufacturing technologies on production economics are largely unknown.

The present study aims to contribute toward answering the following question by considering battery cell production as a specific case: How can the manufacturing costs be improved by new process technologies or general improvement measures?

This study is settled in the field of technology assessment and offers implications for literature on production economics and technology planning. Our work contributes in particular to reducing complexity of technology assessment problems in the light of integrating new and emerging technologies. This is achieved by methodically disclosing the cost structure of battery cell production (as exemplary processing industry) in a generalizable way and elaborating on the impact, which results from the integration of new and emerging technologies. It furthermore adds to the robustness of bottom-up cost modeling by providing validation for the case of real battery cell fabrication. Implications for technology managers, researchers, and policy responses are discussed as well.

The rest of this article is organized as follows. Section II introduces the research work of the present study by first referring to the literature on production economics. Subsequently, existing preliminary work on cost modeling of battery cell production is recapitulated, and special features of the field of battery research are highlighted. This emphasizes the relevance of the topic from the perspective of the academic discipline of innovation and technology management. Section III outlines the case study of a lithium-ion battery cell manufacturing facility analyzed in this study by first discussing its specific background (funding and task profile). Subsequently, actual planning data on the facility layout, the production throughput, cost-relevant equipment specifications, and the production balancing are provided. Section IV describes the chosen methodological approach for cost modeling and discusses it with alternative approaches. Section V provides an overview of production costs and discusses the influence of production-related optimization factors. Subsequently, the influence of technological innovations on production is described, and an outlook on recommendations for action derived from these is given. Finally, Section VI concludes the article with the contributions and limitations as well as recommendations for future research.

II. Literature Review

Meeting cost targets is, besides achieving quality and throughput targets, arguably an essential component of decisions on the use of technologies in the production process. Work in the scientific field of engineering and technology management, which is closely related to the subject of this study, focuses on the development and testing of methodology for problems of technology assessment [14] and decision-making [15], [16]. Although the studies discussed in the following originate from multidisciplinary scientific streams, they provide a solid overview of cost structures in battery cell production as an exemplary manufacturing sector, which is a basis for understanding possible cost-reducing measures in the context of technology assessment.

Even though recent studies have reported annual cost reductions of approximately 8% (between 2007 and 2014) [4] and promising cost levels of \$70–90/kWh for cells and \$150/kWh per pack [17], [18], there are a variety of variables that can lead to the realization of these cost reduction potentials. Different strategies exist to achieve these goals, which have been discussed and investigated in various publications. Thus, in terms of the cost structures of lithium-ion battery cells, it is well known that a large part is due to the sourcing and further processing of battery materials (especially cathode, anode, and electrolyte). Certain studies even see material price as the central limiting factor for the price reduction potential of lithium-ion batteries [12]. Purchasing large quantities to reduce costs per unit quantity are suggested as strategies to achieve cost targets. In addition, in-house production of materials or precursors is under discussion for backward integration along the value chain. This helps extend value creation processing within the company [19], which also involves the establishment of strategic partnerships [6]. Certain researchers have addressed their cost forecasts on battery cells and packs accordingly, examining the impact of battery materials utilized [5], [20], [21]

In addition to the strategic approaches to input factors aimed at increasing cost efficiency, there is a wide scope for actions required to realize cost degression effects. These concern the actual production process, for example, by balancing the production size. Studies that address the size of production scale define a corridor from 200 to 300 MWh/year to 2 GWh/year as the most efficient so far [10], [22]. With the prospect of positive effects of balancing (in this case, the capacitive load of electrode production), larger factories can also be operated in a cost-optimized manner in the future. This effect was quantified as a cost advantage of >$5 kWh-1 [10]. Studies that address the impact of compound effects assume savings of between 9% and 21% per battery pack based on bottom-up calculations [11]. In addition to the design of the size scaling of production processes, the production location, and associated costs due to employee wages, energy prices, building prices, and tax levies are other key issues that influence production costs. Studies attribute a cost difference of $6.4/kWh to the location decision and address factors indirectly affecting production, such as GHG emissions through energy mix, knowledge structure, labor market, and industrial development [23], [24], [25]. Closely related to the approach of using business strategies to reduce material costs is the approach of fostering technological efficiency to optimize resource allocation. For example, studies address critical resources and their alternatives [26] on the one hand, and material recycling opportunities or reusability concepts [27], [28] on the other. Optimization work with the aim of reducing energy consumption [29], as well as elaboration on the digitalization of the production environment and quality assurance have so far been primarily simulation based [30], [31], [32], [33], [34]. The establishment of continuous process control enables a more uniform design of manufacturing stages, potentially leading to lower buffer inventories, and thus, enabling a lean, cost-optimized manufacturing environment [7], [35].

Another way that is widely discussed in academic literature is the integration of technological innovations to substitute or streamline the required inputs. For example, it has been shown that investments in plant equipment show potential savings by eliminating solvent recovery equipment (when processing with NMP). This is enabled by alternative processing routes using aqueous solvents [36]. The use of dry coating processes that eliminate solvents can lead to substantial savings in terms of equipment investment and ongoing costs due to energy consumption [37].

The cell finishing, the process section at the end of the manufacturing chain for lithium-ion battery cells, comprises the steps of formation and cell aging. The formation step refers to the formation of the solid electrolyte interface (SEI), an interface layer at the electrodes of the battery cell that allows physical and chemical thermodynamic processes to take place by applying voltage and running a time- and phase-dependent program [38], [39]. The formation step is particularly quality determining and has an enormous impact on cell performance [6], [40]. However, formation is considered one of the most cost-intensive processes in battery cell manufacturing due to its enormous energy consumption. Therefore, cost reduction strategies often deal with reducing the time of the forming cycles [41]. This holds implications for the energy costs required and involves forming strategies to accelerate the formation of the necessary boundary layer between the electrode and electrolyte [42], [43]. The following examples, among others, are known in the literature as strategies to save time.

1) Narrowing the voltage window of the formation cycle can effectively shorten the formation time [40].
2) The application of pulsed current charging enables a higher charging rate in the formation process, and thus, shortens the formation time [44].
3) The application of simultaneous elevated temperature and mechanical loading resulted in time reductions in the formation process [41].
4) The approach of applying an artificial SEI layer by thin film techniques such as atomic layer deposition, rather than its formation out of the components of the cell (primarily the electrolyte) by formation programs, has so far only been demonstrated on a laboratory scale [45], [46], [47], but may provide a crucial time and energy advantage in the future.

However, these strategies are all still subject to debate in the scientific literature and definitely require further intensive, in-depth understanding of the formulation-dependent physicochemical processes within the cell before they can be applied on a scaled-up, industrial scale [48]. In this regard, the uncertain formation mechanism and composition of the SEI are major obstacles in understanding formation and aging. Studies illustrate that formation programs aiming at time optimization are in tension between minimizing impedance rise, improving capacity maintenance, and avoiding lithium plating [49]. Improper forming processes that are not matched to the conditions inside the cell can lead to uneven formation of SEI or undesirable lithium plating, which result in negative effects on lifetime due to premature capacity degradation and safety risks due to dendrite formation and short-circuit hazards [49], [50], [51], [52]. The development of advanced characterization techniques can contribute to further understanding of the formation, property formation, and aging behavior of SEI, and thus, represents the starting point of time-shortening or energy-saving measures.

As part of the manufacturing process, cell aging is an end-of-line test that has the task of detecting irregular capacity degradation of individual cells over time, and thus, identifying defective cells [42]. Cost-reducing innovations are primarily concerned here with measurement technology and data-based modeling, which are able to detect defective cells more quickly, and thus, contribute to streamlining the overall process [53], [54], [55].

In addition to the possibility of innovating the existing process through technological innovations, a final way to be mentioned is to increase the performance of the cells through product innovations (in this case, optimization of the cell chemistry). This reduces the number of cells required, which indirectly contributes to an increase in efficiency. Solid-state batteries, although highly uncertain due to the lack of real production data, have already been addressed by bottom-up cost calculations and predict, competitive costs in the long term, at least for their subcategory of solid-state sulfide cells [56]. For oxide batteries, the energy-intensive processing step of sintering is considered an obstacle. The aerosol deposition method is shown to be promising and could bring cell technologies down to a cost level of up to \$150/kWh [57]. Implications for their processability and possible optimization potentials by increasing the throughput or reducing the residence time are also discussed [58]. Depending on the intended application, the cell designs can be varied. For example, particularly thick electrode layers, especially for high-energy applications in all-electric automobiles, could lead to a reduced BEV pack cost by an additional 8% [22]. In addition to the variation in the electrode properties, there is further potential for innovation in the design of current collectors. Recent examples consider scientific studies as well as announcements by automotive companies regarding multitab or "tabless" design" [59], [60].

The findings of investigations into the various subaspects of battery cell production are aggregated in studies on the modeling of production costs. For lithium-ion battery cell manufacturing, however, this is not a completely unaddressed topic; thus, earlier works can be referenced. One key dataset used by a variety of studies, particularly for building bottom-up models to replicate battery cell manufacturing costs, is the BatPaC database from Argonne National Lab. BatPaC is a freely available LIB design and cost model that allows the evaluation of different LIB designs and chemistries to be predicted using simulation. This is done based on laboratory data and pack-level metrics. By evaluating the cost of battery packs at specified production levels, it can be used to predict material and energy requirements and to identify opportunities for cost reduction [61], [62]. Duffner et al. [53] provided an excellent overview of the previous research landscape on battery cell manufacturing cost modeling, highlighting the BatPaC model as being the most influential database in this scientific field to date.

Previous studies have highlighted a variety of individual content facets on the part of the impact of cost sensitivity of the selected product or process innovations. However, we observed here that the sources and references cited in many studies contain outdated data or data that have not yet progressed beyond a bottom-up approach [21], [63]. Datasets based on real battery cell production planning data are urgently needed to validate these planning-conceptual approaches. In this study, we follow up on the recommendations for future research by Duffner et al. [64]. Thus, the use of quantitative models for cost calculation, the provision of model architecture and input data, as well as the thematization of novel technologies and calculation of a standard format (21700) are carried out. In addition, our work responds to the call for additional integration of process technology innovations and validation through concrete planning/operational data of a cell manufacturing research factory [7].

Furthermore, since the field of battery cell manufacturing has high innovation dynamics, studies based on current datasets are urgently needed to advance the field and conduct research toward successful technology transfer. Studies indicate that it is more difficult for battery research, exemplified as a subdiscipline of energy technologies encompassing diverse knowledge sectors [65], [66], to integrate innovative technologies into production processes than in comparable manufacturing sectors. This is due to the additional coordination effort of knowledge and its transfer to other use environments (use environments, [67], [68]) (e.g., from research to industrial application, or even use in different end products) [69]. This underpins the relevance of the topic of battery cell manufacturing to the knowledge field of technology and innovation management. Furthermore, it provides a case [70] that is suitable for deriving generalizable conclusions for similar industries involving multisectoral knowledge fields [71]. Discussions on the manifestations of technological change in industry, such as battery cell manufacturing as a multisectoral industrial field have scarcely been discussed so far. The analysis of concrete case studies can offer an added value to built-up knowledge, such as the identification of correlations between innovations of different origins and their influence on production efficiency at the system level. Such insights are helpful in taking a holistic view without disregarding individual technological innovations and their specific contributions. For example, different inputs can often be substituted for each other. Technological innovations that influence production efficiency should be discussed here, as well as novel application conditions that influence the appearance of the end-product, i.e., the battery cell.

III. Setup of Battery Cell Production (Case Study)

In Germany, the federal government is completely funding the construction of a large-scale factory for lithium-ion battery cell production with more than 700 million €, solely for research reasons. Fig. 1 shows a rendered picture of the factory during the earlier planning phase. In this factory, namely the "Research Fab Battery Cells FFB," battery cells shall be produced on an industrial scale, production problems will be identified, and new production technologies will be tested [72]. By setting up this unique technology accelerator, Germany and Europe aim to catch up with their Asian counterparts, which dominate the global battery cell market today. The factory, which is run by the "Fraunhofer-Gesellschaft," will be technically capable of producing up to 7.0 GWh/a of electrodes. This is close to industrial scale (e.g., SK Innovation, Georgia-US, 11.7 GWh/a [73]; Northvolt Zwei, Salzgitter-Germany, 16 GWh/a [74]; and CATL, Erfurt-Germany, 14 GWh/a [75]). Therefore, the "Research Fab Battery Cells FFB" will probably be the largest demonstration factory of its kind worldwide. The factory, which is the basis for this study, is going to be located in Münster, in the west of Germany. Two large state-of-the-art coating lines

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Fig. 1. Rendering of the German research fab battery cell (picture: Artvisu, artur krause).

will be located at the elongated side of the canal. Right next to it, the assembly and formation as well as aging and testing for different cell formats (cylindrical, pouch, and prismatic) will be located. As the mission of this research fab is to gain knowledge about the processing of battery cells, good comparability through the use of a standardized format (such as the 21700 cell) is beneficial toward achieving this goal and the same is also recommended by corresponding literature for the development of further insights into cost modeling and the identification of complex cause–effect relationships [6], [7]. The output of the assembly and forming lines, however, are much smaller than that of the electrode lines, capable of producing 30 cylindrical cells per minute.

The "Research Fab Battery Cell" is the perfect environment for a comprehensive, state-of-the-art production tear down and cost modeling for modern battery cell production. The authors of this study are part of the factory management team and have unique insights in all aspects of cost planning. These insights shall be shared here as far as possible to give researchers as well as managers a reliable theoretical base and primary data for further modeling.

For the production tear down (case study), the exact layout of the research fab was not used, but all data from different planning scenarios and planning stages were utilized to design a state-of-the-art battery cell factory. Battery production and, therefore, the layout common factories usually consist of the following three main phases:

1) electrode manufacturing;
2) cell assembly;
3) cell finishing.

The layout of a state-of-the-art factory (machines and dry rooms) for all three production phases is shown in Fig. 2. The factory has an output of 200 cylindrical cells per minute (ppm), which is approximately 1 GWh/a, depending on the battery cell chemistry. This is a common maximum number for production lines when producing cylindrical cells today. Most factories multiply the number of such "200 ppm production lines" to increase the overall output of the factory. For example, a 5-GWh/a factory will have five times the machines, as shown in Fig. 2. This multiplication has only minor effects on production costs though, as scale effects are minor.

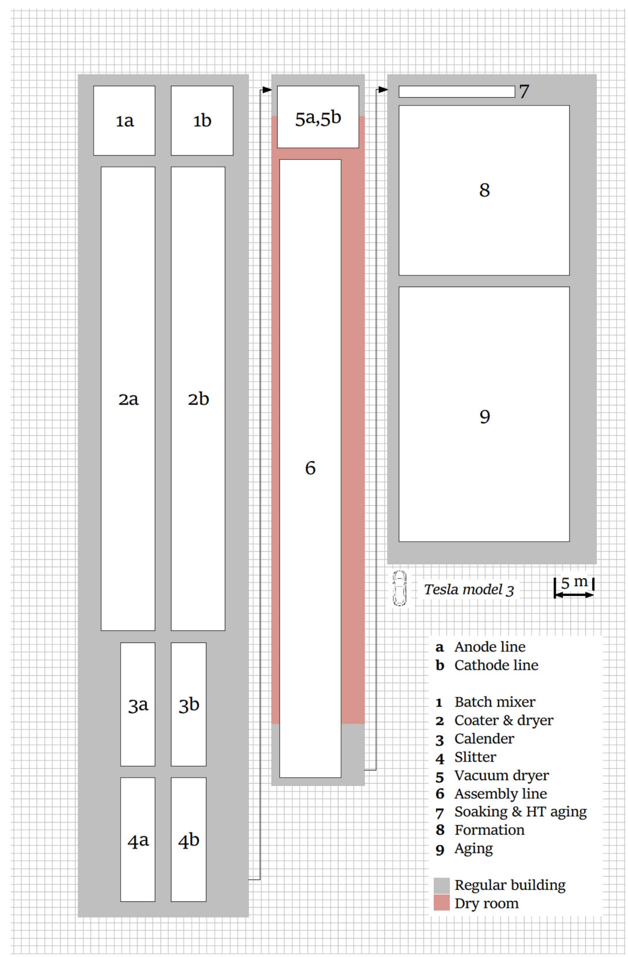

Fig. 2. Layout of a state-of-the-art battery cell factory with an output of 200 cells per minute.

The factory space for storage is not taken into account, as this is a highly case-specific factor and does not result from technical reasons. Rather, it is a decision between risk-taking and economic capital lockup. In addition, the shown layout is not optimized for space saving or material flow. Rather, it shows the required space dimensions for each manufacturing step and

TABLE I
TECHNICAL BATTERY CELL PARAMETER

Parameter	Value	Unit
Format type	Cylindrical	–
Format size	21700	mm
Cell configuration	High power	–
Nominal voltage	3.6	V
Nominal capacity	2.33	Ah
Chemistry cathode	NMC622	–
Chemistry anode	Graphite	–
Coating thickness cathode	42	µm
Coating thickness anode	45	µm
Number of coated sides	2	–
Areal capacity cathode	2.0	mAh/cm²
Areal capacity anode	2.2	mAh/cm²
Separator	Polyolefine	–

makes the production and cost modeling in the following pages easier to understand.

In Table I, the technical specifications of a typical high-power automotive battery cell (used for the modeling) are shown. These are standard values of an average NMC622 battery cell with a cylindrical 21700 format, with the aim of achieving high power rather than high energy. Using a production output of 200 cells per minute, the hourly produced battery capacity is $P_{\text{produced}} = 100.80$ kWh/h.

In Table II, the technical specifications of the production machines and equipment are shown for each production step as well as for the majority of the required infrastructure. In Table III, the relevant costs are shown. This is the major bottom-up dataset used for the cost modeling and scenario analysis later in the text. The data sources include the target price offers from production machine vendors and manufacturers, which were requested during the factory planning process. To ensure high accuracy of the economic and technical data, multiple target price offers were obtained and analyzed. The table shows the average values of two or more offers. In a few cases, the numbers had to be interpolated or extrapolated according to the right production machine size. These numbers are marked individually. As shown in Table II, production machines have different maximum production capacities. Fig. 3 shows the maximum producible output of battery cells and battery components in kWh/h for each production step according to the defined battery cell specifications.

At a first gaze, the production output is not homogenous. However, for economic production, the output of all processes should be at the same level. This is very difficult to realize, as various machines from different vendors are required and have only certain predefined standard machine sizes. Therefore, certain variations in the producible output along the production line are common. In the demo factory, the bottleneck is the assembly line, which has a maximum output capacity of 200 cells per minute (ppm). This is equal to a production output of approximately 100 kWh/h.

The subsequent bottleneck includes the coating and drying processes in electrode production. As coating, drying, calendaring, and slitting are continuous roll-to-toll processes, the production output of calendaring and slitting is limited, although the machines are capable of (much) higher productivity. To ensure

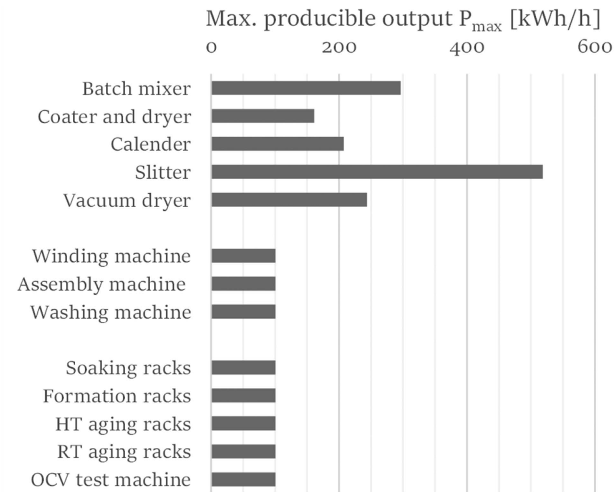

Fig. 3. Maximum producible output of battery cell components $P_{\max}$ for each production step.

uninterrupted production, the outputs of mixing and vacuum drying are designed to be slightly larger by purpose, as these are processes with single large batches. Later in the article, we will discuss the effect of a perfect homogeneous production flow on production costs.

IV. Methodology and Cost Model

Hueber et al. [77] divided the existing research landscape on battery cell manufacturing cost modeling into qualitative (intuitive and analogy based) and quantitative methods (parameter based and analytical). Analytical models are generally considered to have a higher level of detail and transparency [7]. Certain case-based approaches to the further development of cost models focus on their generalizable applicability across industries. For example, the case-based reasoning method is advantageous in terms of its ability to accept unknown information, take into account the results, and the ability to process certain cases [78]. Other cost-analytic studies deliberately focus on the uniqueness of construction and design practices of different fields and encourage recognition that the economic competitiveness of any technological choice depends on the context of its application [79]. Related to the context of battery cell manufacturing, analytical bottom-up models have proven to be useful in illustrating the cost-causing structures of processing. A widely used approach is the process-based cost modeling (PBCM) technique [7], [13], [19].

Studies have addressed the general shortcoming that while the most effective way is to derive cost positions from the design of the products and processes themselves, cost data are rarely available for product/process designers in a usable form [80]. Thus, the analysis of the study presented here is fundamentally based on a bottom-up approach to cost modeling, which involves accounting for the influence of a wide variety of processing and product design variables within the calculation. Previous works have suggested a PBCM-based approach for calculation

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TABLE II
MACHINE AND PRODUCTION PROCESS RELATED COSTS (REFERRING TO [76])

Process step (-) [-]	**Process number (j) [-]**	**Machine/Process (-) [-]**	**Investment costs (IC) [€]**	**Electric energy consumption ($E_{electric}$) [kWh]**	**Gas energy consumption (E_{gas}) [kWh]**	**Dimensions (w×l) [m×m]**	**Areal footprint ($A_{footprint}$) [m²]**	**Required worker (n_{worker}) [-]**	**Max. producible output (P_{max}) [kWh/h]**	**Dry room**	***Appendix: max. performance parameters***
Electrode manufacturing (anode)	1a	Batch mixer	1,080,000[1)]	20	-	8×9	72.0	1	302.38	no	*250 l/h*
	2a	Coater and dryer	5,500,000	75	825	7×60	420.0	2	179.63	no	*30 m/min × 0.7 m*
	3a	Calender	2,900,000	*60*	-	4.5×16	72.0	1	228.10	no	*30 m/min × 0.8 m*
	4a	Slitter	1,150,000	45	-	4.5×16	72.0	1	570.24	no	*80 m/min × 0.75 m*
	5a	Vacuum dryer	1,200,000	5	210	6×8	48.0	1	267.78	partly	*3x4 Coils, a 4900 m*
Electrode manufacturing (cathode)	1b	Batch mixer	1,235,556[1)]	20	-	8×9	72.0	1	296.19	no	*250 l/h*
	2b	Coater and dryer	5,500,000	75	825	7×60	420.0	2	163.30	no	*30 m/min × 0.7 m*
	3b	Calender	2,900,000	*60*	-	4.5×16	72.0	1	207.36	no	*30 m/min × 0.8 m*
	4b	Slitter	1,150,000	45	-	4.5×16	72.0	1	518.40	no	*80 m/min × 0.75 m*
	5b	Vacuum dryer	1,200,000	5	210	6×8	48.0	1	243.43	partly	*3x4 Coils, a 4900 m*
Assembly	6	Winding machine		25	-				100.80	yes	*200 ppm*
	7	Assembly machine	9,000,000[3)]	160	-	8×80 [3)]	640.0 [3)]	5 [3)]	100.80	yes	*200 ppm*
	8	Washing machine		200	-				100.80	partly	*200 ppm*
Formation	9	Soaking racks		-	25	1.5×2,1	3.2		100.80	no	*4h, 200 ppm*
	10	Formation racks		1000	-	20×24	480.0		100.80	no	*20h, 200 ppm*
Aging	11	High Temp. aging racks	45,000,000[2),3)]	-	40	1.5×13.3	20.0	4 [3)]	100.80	no	*24h, 200 ppm*
	12	Room Temp. aging racks		-	-	24×30	720.0		100.80	no	*504h, 200 ppm*
Testing	13	OCV test machines		100	-	2×7.5	15.0		100.80	no	*1h, 200 ppm*
Miscellaneous	14	Material handling machines		200	-	-	-		100.80	no	200 ppm
Dry room	-	Dry room	5,000,000	163	913	12×80	960	-	-	n/a	*-40°C dew point*
Building	-	Building /shop floor	11,440,000	-	-	n/a	5200	-	-	n/a	

[1)] Values interpolated, [2)] Values extrapolated, [3)] Data for entire set.

TABLE III
FURTHER COSTS AND INFORMATION

Parameter	**Variable**	**Value**	**Unit**	**Note**
Labor costs	PC_{worker}	40.00	€/h	For location Germany
Energy costs (electricity)	$CC_{electric}$	0.151	€/kWh	For location Germany
Energy costs (gas)	CC_{gas}	0.023	€/kWh	For location Germany
Area unit costs	$AC_{building}$	0.008	€/m²/h	For location Germany
Overhead rate	$i_{overhead}$	60	%	Based on personnel costs
Production time	-	8760	h/year	Quasistatic 24h × 7d production
Deprecation time machines	$t_{depreciation\_m}$	10	years	
Deprecation time building & dry rooms	$t_{depreciation\_b}$	30	years	

of battery cost [7], which we validate via the analysis of a consistent data set from the real planning work of a battery cell production and complement as well as with a discussion on the cost impact of emerging technologies [80]. In this PBCM technique, a bottom-up approach introduced by [79], costs are modeled in the following three steps:

1) process model;
2) operations model;
3) financial model.

In the process model, the product and its features that should be manufactured are transferred into a technical production layout and its technical parameters (Fig. 2 and Table II). In the operations model, the operating conditions are transferred into resource requirements (Tables II and III). In the financial model, the resource requirements are then transformed into financial KPIs. This is done as follows: To calculate the battery cell production costs in €/kWh, we propose the following calculation:

$$C_{\text{total}} = \sum_{j=1}^{n} C^{j}_{\text{direct}} + C_{\text{indirect}}. \quad (1)$$

First, we differ between direct and indirect costs. All costs are allocated to one produced kWh battery capacity (€/kWh). The direct costs are allocated to each individual manufacturing process (j) for a continuous output of 200 cells per minute (respectively 100.80 kWh/h). The direct costs are calculated as follows:

$$C^{j}_{\text{direct}} = C^{j}_{\text{machine}} + C^{j}_{\text{energy}} + C^{j}_{\text{labor}} + C^{j}_{\text{footprint}}. \quad (2)$$

In direct costs, material costs are not taken into account, as these costs are highly individual and can significantly affect the cost model. Material costs can be added later by each individual researcher, if required. The indirect costs are calculated as follows:

$$C_{\text{indirect}} = C_{\text{building}} + C_{\text{dry room}} + C_{\text{overhead}}. \quad (3)$$

The equations for the detailed calculation can be found in the appendix. As shown in Fig. 2, the entire factory is planned in the spirit of lean production. Thus, costs that do not result in value creation are minimized.

In this article, all relevant input data and values are named in absolute numbers. Thus, each researcher can recalculate the presented results using them. More importantly, each researcher

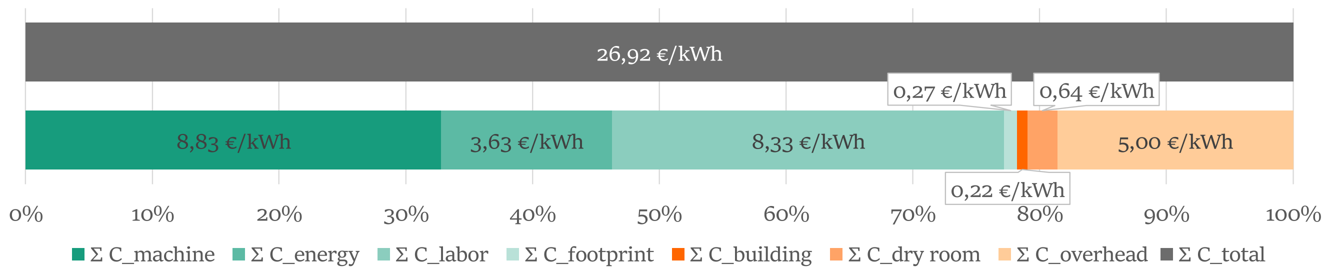

Fig. 4. Structure of total costs (C_{total}) for battery cell manufacturing (basic case).

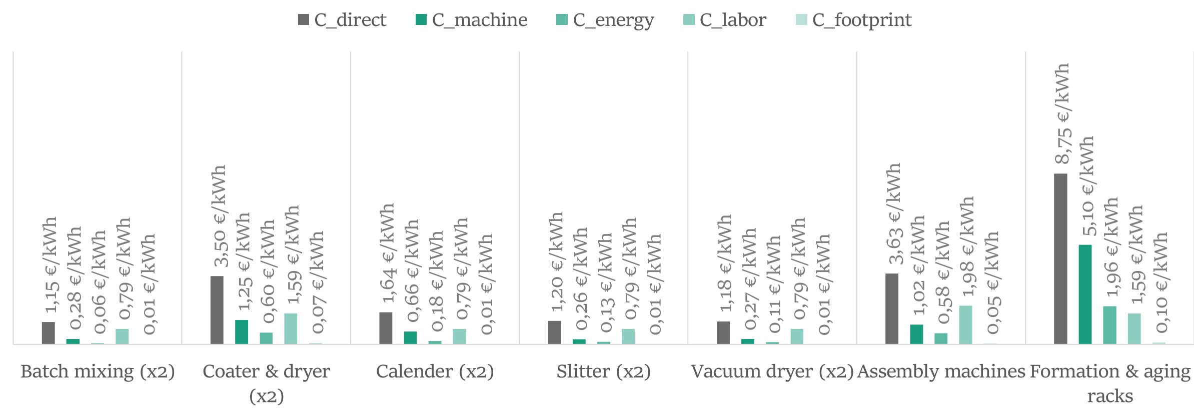

Fig. 5. Structure of direct costs (C_{direct}) for battery cell manufacturing for each production process (basic case).

can use the values of this basic factory layout to modify, extend, or update their own models.

To demonstrate the capability of this detailed model and of the given dataset, the following will be calculated, presented, and analyzed:

1) costs with reference production (case study);
2) costs with optimized production;
3) validation/comparison of calculated costs;
4) costs with future technologies.

First, we will analyze how much the manufacturing of the battery cell will cost and what are the major cost drivers with the presented factory. Second, the impact of optimizing production and production locations will be analyzed. In the third step, these results will be compared and validated with other and known cost calculations. Fourth, the impact of novel cell and production technologies on industrial readiness will be analyzed for the forthcoming years. Through this, we demonstrate not only the validity of the model and the dataset but also the capability to predict the state-of-the-art costs as well as future battery cell costs.

V. Results and Discussion

A. Costs With Reference Production (Case Study)

For the basic case, we assume that the factory is located in Germany, Europe. As Germany is located in the heart of the European market and is also a major player in the automotive industry, many cell factories are being built there at the moment (production capacity of up to 500 GWh/a has already been announced for 2030 [3]). However, Germany has high labor costs, high energy costs, and high building costs. Fig. 4 shows the cost structure of C_{total}. It is shown that in this production plant, the production of 1 kWh battery capacity costs 26.92 €. The main cost drivers are costs for machine depreciation, followed by labor and energy costs. The costs for the footprint and building are negligibly small. Thus, even when taking further storage space into account, which was not done here, this would most likely have no significant effect on the total cost.

Fig. 5 shows the cost structure of C_{direct} for the different production steps. Costs for multiple machines have already been considered in the cost structure. It is shown that cell formation is the production step that makes the highest contribution to cost, followed by coating and drying, and then assembly. The reason for this cost peak is that the formation and assembly consist of many single process steps, such as electrode manufacturing, which are summarized here. Nonetheless, formation contributes approximately 45% to the overall direct cost, which is quite large. However, here we are analyzing only the basic case, and further improvement will be taken into account in the following sections.

B. Costs With Optimized Production

As already indicated, there are certain general possibilities for improving the production of battery cells. These include the following:

1) homogenize the production output;

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

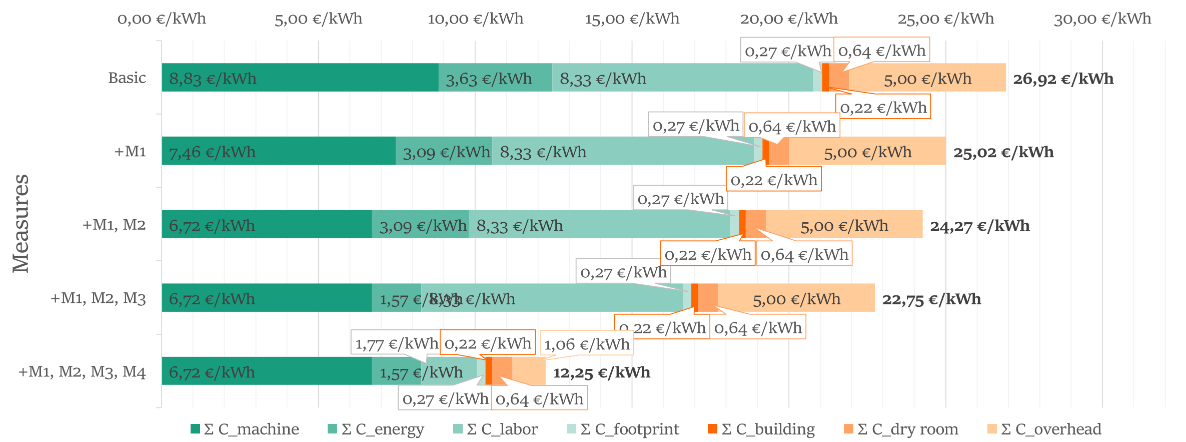

Fig. 6. Effect of optimization measures on battery cell production costs.

2) reduce investment costs for machinery;
3) location with lower energy costs;
4) location with lower labor costs.

1) As shown in Fig. 3, the output of the production processes along the manufacturing chain is not perfectly homogenized. This means that a full capacity load is not achieved for each individual process step. It would be desirable to optimally coordinate the process steps with each other to achieve maximum individual capacity utilization and possibly avoid excessively high investment costs. This is theoretically possible, though, when buying machines in high numbers; for example, to equip a factory with >10 GWh/a production output. To calculate this effect, the output was leveled at exactly 200 ppm here (= 100.80 kWh/h). For calculation purposes, the machine investment costs and energy consumption were linearly interpolated. As we are discussing only about minor changes in machine size, a quasilinear approach is allowed from our perspective. The staff number and footprint are kept the same.
2) Besides that, there is still potential, to decrease the investment costs for machinery further. The battery cell production described in the case study in this article is currently still under development. The investment costs listed in Table II are the prices obtained at the beginning of the negotiation phase. As negotiations progressed, different price reductions in the range of 5%–20% have been achieved so far. Differences lie in the offer of standardized products, such as analytical equipment, for which higher price reductions could be negotiated than for individual products. One reason may be that the supplier's personnel costs are higher for such products, as there is a greater need for adaptation to customer requirements. According to our sources, entire production lines (electrode manufacturing, assembly, forming) with a capacity of 200 ppm can be purchased for 60–80 million €. Regarding total average costs, we have, therefore, made the experience that a 10% discount compared to the initial price on the investment costs for machines is feasible.

TABLE IV
MEASURES TO OPTIMIZE CELL PRODUCTION

No.	Measure	Basic	Optimized
M1	Machine outputs	Variable	$P_{produced}$
M2	Machine costs	100%	90%
M3	Electricity costs	0.151 €/kWh	0.069 €/kWh
M4	Labor costs	40.00 €/h	8.50 €/h

3) Energy is a major cost driver in battery cell production. Thus, many cell factories are built in countries with low energy costs. Examples for Europe are the Scandinavian countries, particularly Norway, with electricity costs of 0.041 €/kWh [81]. However, labor costs are also quite high, which is why an alternative location might be China, where electricity costs 0.069 €/kWh [82].
4) In addition, labor costs constitute a major part of the overall cell cost, especially when analyzing a factory at a location in a high-wage country in the heart of Europe. Thus, by relocating the factory to a country with a lower labor cost, cost reduction is possible (labor costs in China: 8.50€/h) [83]. Table IV shows the quantitative assumptions and measures for an optimized battery cell production scenario located in China instead of Germany. Fig. 6 shows the effects of cost reduction measures on the battery cell cost.

It is shown that by optimizing M1 (production output homogenization) and measure M2 (machine purchase optimization), production costs can be reduced, but only to a minor extent. The most significant effect can be realized by reducing energy costs (M3). By optimizing M1, M2, and M3, the cost of cell production can be reduced significantly to 22.75 €/kWh. Finally, by reducing the labor costs (M4), further reductions can be realized. By applying these measures, a cell production cost of 12.25 €/kWh can be achieved today.

C. Validation

All aforementioned numbers were calculated using the presented bottom-up model and the given input data. To validate the model and the numbers, the calculated results are compared

TABLE V
REPORTED BATTERY CELL COST (INCL. MATERIAL)

NMC battery cell cost	Year	Source
93 €/kWh; 112 $/kWh	2019	[84]
88 €/kWh; 106 $/kWh	2020	[7]
85 €/kWh; 102 $/kWh	2020	[8]
83 €/kWh; 99 $/kWh	2020	[85]
77 €/kWh; 92 $/kWh	2020	[3]

TABLE VI
REPORTED CELL PRODUCTION/MATERIAL COST RATIO

Production/Material	Year	Source
26%/74%	2016	[86]
25%/75%	2018	[6]
30%/70%	2018	[87]
30%/70%	2019	[88]
35%/65%	2019	[89]
35%/65%	2020	[3]
20%/80%	2020	[9]
23%/77%	2019	[84]
23%/77%	2021	[7]

with known price calculations from the research community and market research. Before doing so, it must be taken into account that the following cost drivers, besides the material, are not considered in our presented model:

1) scrap rate;
2) larger maintenance costs;
3) larger maintenance time.

The reason why these are not considered here is that the named factors differ strongly between manufacturers and are difficult to quantify reliably. Thus, realistic production costs are probably slightly higher than the costs calculated via the proposed model. We estimate that the calculated prices for battery cell production are about 10% higher when taking scrap rate and larger maintenance into account.

Many battery costs available publicly are for the cell or pack level, taking into account production costs and material costs [7], [21]. State-of-the-art costs for battery cells are slightly above 100 USD, although 2020 was the first year when costs below 100 USD were reported; see Table V.

Selected studies, in addition to summing up the total costs of cell manufacturing at the cell level, also address the breakdown between material, process, and other costs. There are values given in the literature that describe the ratio of battery cell cost between material and production costs. Common ratios are shown in Table VI.

Although the ratio differs from source to source, a proportion of manufacturing cost of 20%–35% seems to be common. By combining the average battery cell cost and the production/material cost ratio, a cost range of 14.40–32.55 €/kWh for battery cell production is identified. This is quite exactly the cost we calculated with our model (optimized to basic scenario: 12.25–26.92 €/kWh). However, in our optimized scenario, we identified slightly lower production costs. But we did not consider the scrap rate in our calculations. In general, there is a strong match between our bottom-up based results and those of the state-of-the-art literature and market research. Against this background, our cost model seems to be valid and covers the latest state-of-the-art production technology.

D. Costs With Future Technologies

After having shown that the model provides results that fit to common cost values, we shall investigate how battery cell production and cost structure can look like in the near future. For this, not just theoretical ideas (e.g., increasing coating thickness), but genuine aspirations of the manufacturing industry are analyzed. The most important approaches today include the following:

1) NMC811 & SiO/C cell chemistry;
2) tabless electrodes and continuous coating;
3) dry coating technology.

NMC811 cell chemistry for cathodes is currently replacing the NMC622 cathode chemistry. This is an ongoing process, and the first battery cells with NMC811 cathodes are already on the market. Thus, NMC811 represents current state-of-the-art to the best of our knowledge [3]. In terms of production costs, a major benefit is the higher specific capacity of NMC811 (200 mAh/g) than that of NMC622 (170 mAh/g). In addition, the material is cheaper because of the reduced amount of cost-intensive cobalt required. The challenges in using NMC811 in production are related to the electro-chemistry and high requirements for the dryness of the production environment. However, recent studies highlight the massive potential of "cobalt-free" lithium-ion batteries for a more sustainable manufacture of electric vehicles in the coming decades [90].

In addition, the cell chemistry on the anode side has been further developed to SiO/C cell chemistry with a silicon oxide content of 5%. The composite electrodes lead to increased volumetric energy densities, since SiO has a specific capacity (2400 mAh/g) that is almost seven times higher than that of C [91], [92], [93]. By utilizing it, the specific capacity of the anode (graphite: 360 mAh/g) can be increased (SiO/C with 5% SiO: 460 mAh/g). The SiO/C layer thickness of the anodes can be designed thinner and/or the cathodes thicker depending on the application (HE/HP). In our future scenario F1, we assume the same physical design of the cell as shown in Table I, but with NMC811 on the cathode side and SiO/C (with 5% SiO) on the anode side. With regard to the production costs, it can be stated that less material is required per kWh produced. For such a cell, with a production output of 200 cells per minute, $P_{\text{produced}} = 118.6$ kWh/h of battery capacity can be produced instead of $P_{\text{produced}} = 100.8$ kWh/h.

Another approach to reduce production costs is multitab or "tabless" battery cell production and cell design. A tabless design involves cylindrical battery cells, which provide benefits in terms of battery cell performance and production performance. Studies report of benefits in cell performance in multitab instead of single-tab design by +23% SoC fast charging efficiency [59]. Using tabs in cylindrical cells limits their production in two ways. The first is the limitation of the tab-welding process in cell assembly. Second, and even more important, is the limitation of coating during cell production. For a cylindrical cell design with tabs, it is required that the electrodes have free surface areas that are not coated. This coating has to be interrupted frequently, which limits the coating velocity considerably. The coater, shown in Table II, has a maximum coating velocity of $v_c = 30$ m/min in discontinuous mode and $v_c = 80$ m/min in continuous mode. Thus, using a tabless design, the coating velocity can be almost tripled. However, a new bottleneck related to the length of the dryer (here, $l = 40$ m) occurs. When the coating velocity is increased and the drying time is kept constant, the dryer length must be increased. For a 40-m long dryer, coating velocities of $v_c = 50$ m/min are possible. However, for a coating velocity of $v_c = 80$ m/min, an extended dryer length of about 70 m is required.

In our future scenario F2, we increase the coating velocity from $v_c = 30$ m/min to $v_c = 50$ m/min. This affects the required machine size, investment costs, and energy consumption. Similar to M1, staff number and footprint are kept the same. Moreover, the data of the assembly line are kept the same. This is because tab welding is not a major bottleneck in assembly. Although tab welding is eliminated, a connection still needs to be generated by another machine. Therefore, the effect of the tabless design on the assembly costs is probably negligible. Since tabless design is an innovation in cell design, the corresponding advantages are to be found at the cell level. While material innovations primarily aim at the realization of higher energy densities, cells with tabless design enable the realization of higher power densities. This can be explained by the fact that there are shorter diffusion paths of the electrons to the current collectors of a cell, and thus less heat development and other attractive electrical effects occur inside the cell. This is indicated by previous studies on tab designs [94]. In addition to the cell-level benefits, the application of tabless design also enables the realization of increased volumetric energy density at the pack level by reducing the free space between cylindrical cells. A recent, prominent example that is announced to use tabless design is the codeveloped 4680 cell from Panasonic and Tesla [2]. However, the fundamental cell design is not new, since examples of commercially available cells from the past can be found, e.g., SAFT's VL6P-cell, patented in 2005 [95].

Another future battery cell technology is dry coating [96]. As shown in Fig. 5, coating and particularly drying constitute the main cost driver in electrode production. By dry coating, no extensive NMP solvent recovery is required and neither energy-intensive nor space-intensive drying is required. However, dry coating technology is still in development. One of the technology leaders is probably Maxwell Technologies, Inc., which actually originates and gained experience from the production of capacitors. Other dry coating technologies are, e.g., the dry transfer process [97], the dry extrusion process [98], the fluidized bed process, isothermal pressing [99], various deposition techniques [100], etc.

In our future scenario F3, we assume that in dry coating, the investment costs for coater, dryer, and NMP recovery are halved. Dryer and NMP recovery are no longer needed but machine manufacturers will also use technological leadership for high prices. We believe that dry coating machines require slightly more electricity ($E_{\mathrm{electric}} = 50$ kW) due to the higher forces during coating; however, no gas is required for drying ($E_{\mathrm{gas}} = 0$ kW). In addition, the areal footprint is significantly reduced from $A_{\mathrm{footprint}} = 420$ m^2 to $A_{\mathrm{footprint}} = 70$ m^2.

In Fig. 7, the effects of the future scenarios F1 (new cell chemistry), F2 (tabless design), and F3 (dry coating) are shown. The basis for the calculations is the optimized scenario with applied improvement measures M1, M2, M3, and M4.

It is shown that by using an NMC811 & SiO/C cell chemistry, the production costs per kWh can be reduced significantly by almost 17%. Even though the absolute production costs are the same, the relative costs per kWh can be decreased owing to the higher energy density of the cell. With such a chemistry, a cell production cost of 10.15 €/kWh is feasible.

By using a tabless cell design and NMC622 & C chemistry, the production costs can be reduced by approximately 5% to 11.55 €/kWh. This is because a tabless design mainly reduces the coating cost in production. This has a positive effect, but there are also other cost drivers in the overall production, which limit the overall effect.

By using dry coating, further cost reduction is possible. In comparison to standard wet coating with NMC622 & C chemistry, production costs can be decreased by 6%–7% to 11.34 €/kWh. This is for the same reasons as those when using the tabless cell design for production.

When combining all three future measures (F1, F2, F3), according to our calculations, production costs can be decreased to as much as 9.52 €/kWh, a 21% decrease over current prices predicted by our model. Of note, it is remarkable that the effect of tabless design and dry coating is only minor when using NMC811 chemistry ($\Delta C_{\mathrm{total}} = 0.63$€/kWh). Nonetheless, it has to be taken into account that both measures not only have an effect on the production costs but also on the battery cell performance/parameters.

With a tabless design, e.g., the thermal load during charging and discharging is lower. This positively affects C-rates, lifetime, etc. In addition, larger cell diameters are possible, which again positively affects production costs. Similarly, dry coating technology significantly reduces the energy demand in production, and therefore, positively affects the CO_2 footprint. This has become increasingly important from a societal and political perspective. However, having said this, the major outcome here is that, by our calculations, cell production costs at around 11.00 €/kWh appear to be realistic within the next few years. Fig. 8 shows the breakup of these costs, and the direct cost C_{direct} in detail.

Here, only the direct cost ($C_{\mathrm{direct}} = 8.12$ €/kWh) is shown. The indirect cost ($C_{\mathrm{indirect}} = 1.41$ €/kWh) is less relevant. It is shown that formation is by far the largest cost driver. In particular, the machine depreciation costs (C_{machine}) and energy costs (C_{energy}) are here to name. Approximately 1000 formation racks are required to form an output of 200 ppm for a duration of 20 h. While these are high investment and energy costs on the one hand, on the other hand, the lead time is very high (compare Table II). Thus, the cost per kWh is also high, as no real-scale effects can be obtained. Thus, intensive focus needs to be devoted to formation for further reducing battery cell production costs in future.

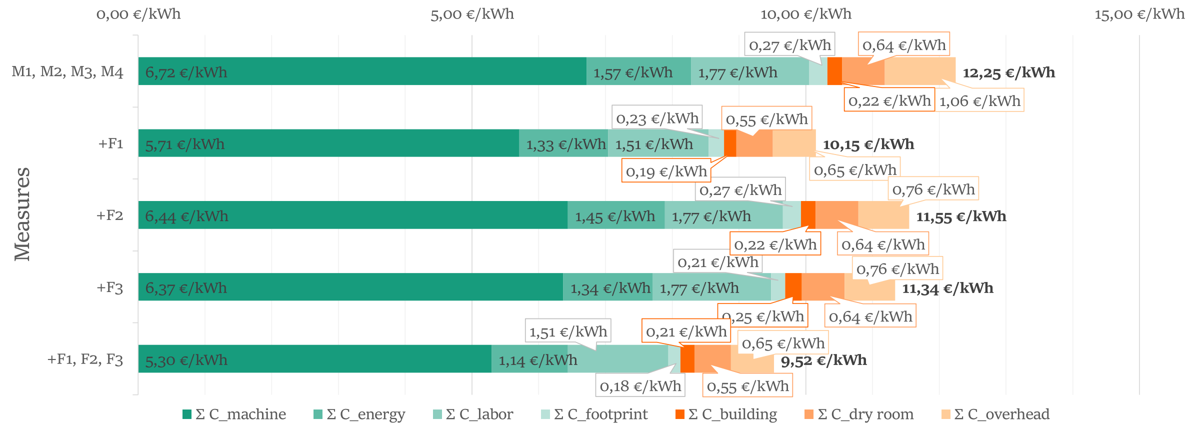

Fig. 7. Effect of future production technologies on battery cell production costs.

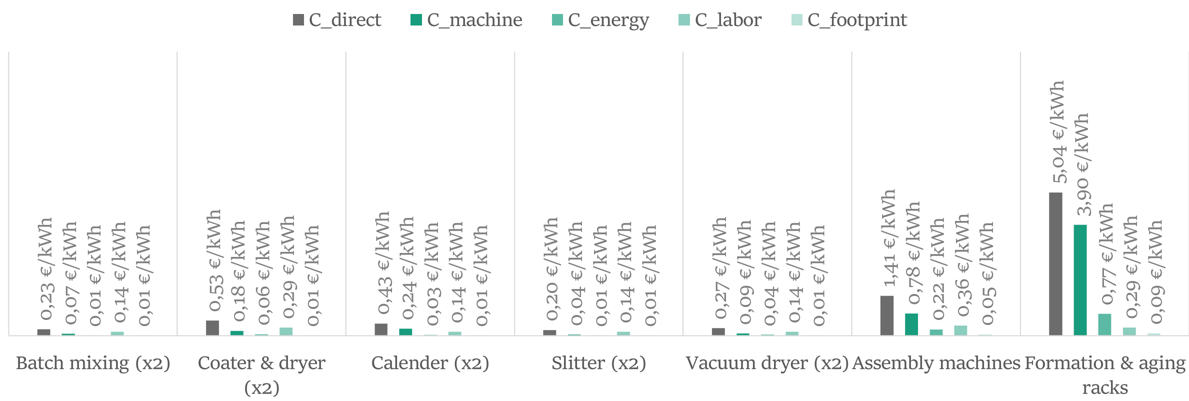

Fig. 8. Structure of battery direct cost (C_{direct}) for battery cell manufacturing (future cases: F1, F2, and F3).

E. Critical Discussion

We have shown that our cost model and our dataset are suitable for reliably calculating the state-of-the-art battery cell production costs. We have also shown that our results fit very well with the latest cell production costs sourced from literature and market research. Nonetheless, there are certain issues that are not taken into account within the model, which should be mentioned and assessed here.

As already mentioned, the scrap rate and larger maintenance costs are not considered in our model. Both vary highly from case to case and depend on the production skills and know-how. Besides, there are no reliable data available for the same. The common rates we notice in discussions are 5%–10% but without any evidence. Thus, we decided to not take the scrap rate into account. In addition, we did not consider larger maintenance costs, as this also varies from case to case and standard maintenance is already considered in the overhead costs.

In our lowest-cost scenario, the factory is located in China. Due to attractive cost structures, the scenario of processing battery cells in the Far East and subsequent international logistics has been pursued on a large scale in the past. The transformation of the automotive industry toward electric mobility underlines the associated need to keep the added value of the final product within the corporation. Announcements of the manufacturers for the conclusion of a significantly higher demand for battery cells to be manufactured locally, close to the customers. Compliance with the legally stricter regulations and standards of the automotive industry in the direction of sustainable manufacturing also suggests this development.

In such a case, new production technologies, such as dry coating, will have far higher economic benefits than those shown here. This also needs to be taken into account when working with our cost model and assessing results. Because the energy demand for dry coatings is generally very less compared to conventional wet coatings, the technology allows production activities to be more independent of the respective local energy costs. As a result, the technology has the potential to establish itself globally, which could lead to its further development, leading to even lower per-unit costs.

With increasing focus on the environment by the society, the topic of "green" manufacturing has become increasingly important. In Germany, CO_2 emission certificates will cost 55€/t-CO_2-eq in 2025 [101]. As battery cell production requires a high amount of energy, not just electricity, but also natural gas, this will be a significant future cost driver. This also has to be considered when working with the proposed model. We did not do so because emission regulations vary widely across the world.

Finally, yet importantly, we want to underline that the future production technology approaches we have presented have primary benefits in terms of cell performance parameters. While they affect production costs positively as well, they do so only in a minor way. Thus, this study should not cause doubts or hesitations in terms of new production technologies. Especially in high-wage countries and countries with expensive but "green" energy, these new technologies hold promise to be "game changers" in terms of production costs.

F. Future Outlook

Based on our analysis, we see two main levers to decrease battery production costs: 1) improving the cell finishing process and 2) improving cell chemistry. Both are research topics related to chemistry rather than engineering. While the interaction of the individual components within the cells is optimized in research work on more efficient cell chemistries in order to realize ever higher energy and power densities as well as lifetime, a distinction must be made in cell finishing between the formation process and cell aging. In the formation process in particular, the key knowledge lies in the sequence of a recipe-specific formation program that is aligned to the interaction between applied current, time, and temperature with the chemical processes inside the cell, defined by the material use of additives, electrolytes and the cell format per se, to form a stable boundary layer, the SEI [39], [47].

The formation of a stable SEI is largely determining the quality of the final cell not only in terms of energy and power density but also regarding lifetime and safety issues [6], [40]. While the optimization work on the formation program has rather low requirements for innovative hardware, the potential for energy savings through the introduction of advanced power electronics has been reported though. Former studies report a high energy consumption in the formation process that is not only due to the thermodynamic formation of the SEI, but also to dissipative energy losses during charge/discharge cycles and cooling to maintain a constant temperature and homogeneity between all cells [76].

In cell aging, the cost-causing (Cpex for aging infrastructure, footprint of aging infrastructure) problem arises from the enormous amount of time (3 weeks) that cells are tested for irregular capacity degradation. Here, innovative measurement methods, e.g., advanced self-discharge measurement technology [102], can help to detect defective cells at an early stage, to streamline the overall manufacturing process by selling the cells faster and thus to significantly reduce the need for infrastructure (extensive storage facilities).

Furthermore, automation and the setup of digitization techniques are important measures that can be taken to reduce failure probability, understand causal relationships between processes and can reduce personnel costs further, especially in high-wage countries [103]. Another measure is to reduce the amount of energy required for production. CO_2 emissions will become more expensive and will also be legally restricted in the future. These are future production costs that need to be considered today.

In addition to this technology-oriented outlook, we would like to provide an outlook of what can be done with our basic model in the future. Suggestions for further research are as follows:

1) life cycle assessment of battery cell production;
2) economic assessment of different production locations;
3) assessing the economic impact of new production technologies and new cell technologies;
4) battery cell cost scenario analyses;
5) enhancement of the model by adding new or further improving parameters;
6) identification of future cost drivers.

We hope that our model and, particularly, the dataset contribute to the research community involved in fields related to product manufacturing, especially battery-related research and production management.

VI. Conclusion

In this article, we presented unique insights into battery cell production, including a corresponding technical and economic dataset as well as a cost calculation model capable of illustrating cost-cutting production scenarios for evaluating contributions of new and emerging technologies to business strategy alike [104]. Based on real battery cell factory plans, we derived a state-of-the-art demo factory setup, both technically and economically. For this battery cell factory, we showed the calculation of the battery cell production cost per kWh for different scenarios. We showed that our calculated battery cell production costs match very well with the reported production costs sourced from the latest market research. Thus, we were able to validate the model as well as the factory setup and dataset. Subsequently, we analyzed how battery cell production costs can be decreased further in the near future by using new technologies and cell chemistry. We identified a minimum cell production cost level of approximately 14.00 €/kWh with currently established technology and approximately 11.00 €/kWh with latest/upcoming technology.

Our work contributes to reducing complexity related to the integration of new and emerging technologies by methodically disclosing the cost structure of battery cell production at system level in the sense of an anticipatory technology assessment. We add to the methodology of technology assessment by extending PBCM technique with cost-reducing production scenarios and testing their applicability using real planning data. From our analysis, we can derive implications for strategic technology planning by linking the technology planning mode with the respective level of technological maturity. We can confirm former research results, which relate an increased planning risk for architectural and radical design changes to the product and process system level of battery cell production (e.g., dry coating), since an increasing complexity (also on product level) results out of multiple fields of knowledge involved [105]. We contribute to the knowledge field of technology management by showing which key performance indicators are applied at different dimensions (cell, process, and system level) within battery cell manufacturing and how these are interrelated. By applying the cost model, we showed the impact of current technological innovations in battery research on process design. In doing so, we bridge the gap between research efforts to optimize product properties at the battery cell level to production-related quality criteria and contribute a transferable case study for cross-disciplinary innovations.

Apart from further broadening the subject of cost structures in battery cell manufacturing, another cornerstone of the investigation at hand relates to the disclosed factory layout/setup and corresponding primary dataset. Based on this tangible dataset of real battery cell production, practical implications can be derived. Using these results, depending on their discipline, researchers would be able to, for example, better allocate the need for investigations on specific phenomena from the field of engineering and technology management to the subject of battery cell production, or direct their activities in the field of materials research in a more targeted, that is, exploitation-related manner.

Implications for managers engaged in the battery cell manufacturing industry are that our approach to cost modeling and the datasets of battery cell manufacturing addressed here serve as a basis for benchmarking own activities and measures. As such, a more profound knowledge of the reference production configuration can contribute to successfully increasing production efficiency as well as integrating novel products and services. The findings of our study will enable policymakers to draw conclusions about the cross-relationship between innovations at the material, process, and system levels and the development of funding programs that are tailored to meet these needs for future technology development more effectively.

In a broader scope, our case reflects a multifaceted example on how the role of technological change in industries involves multisectoral knowledge fields and emphasizes the need to adapt institutional structures and processes for promoting innovation more flexible, yet optimization driven, and guiding toward ambidextrous innovation strategies. The study is based on a dataset of a real case study representing battery cell production during development. Thus, the scope of this study is limited to the field of battery cell production. The linking of aspects of product design with those of process design may be completely different in other manufacturing industries. Subsequent studies should attempt to draw on the theoretical base of this article to abstract more generalizable methodological approaches. Further follow-up studies may seek to incorporate learning and optimization efforts with respect to actual plant operations, evaluation of their effectiveness, and retrospective observation of the effects of process innovations on cell costs. Since the boundaries between economic and ecological/social realms are becoming increasingly blurred, especially with regard to the different dimensions of sustainability [106], a subsequent study that extends the approach presented here with corresponding KPIs would be desirable.

Appendix

Exchange rate for all calculations: 1.00 € = 1.20 US$

Assumption: production runs 365 days a year, 24 hours a day

$$C^j_{machine} = \frac{IC^j}{t_{depreciation\_m} \cdot P_{produced}}$$

IC^j	investment costs [€]
$t_{depreciation\_m}$	machine depreciation time [h]
	here: 87 600 h (10 years)
$P_{produced}$	hourly produced battery power [kWh/h]
	here: 100.80 kWh/a (200 cells per minute)

$$C^j_{energy} = \frac{E^j_{electric} \cdot CC_{electric}}{P_{produced}} + \frac{E^j_{gas} \cdot CC_{gas}}{P_{produced}}$$

$E^j_{electric}$	energy consumption of electricity [kWh]
E^j_{gas}	energy consumption of gas [kWh]
$CC_{electric}$	consumption costs for electric energy [€/kWh]
CC_{gas}	consumption costs for gas energy [€/kWh]

$$C^j_{labor} = \frac{n^j_{worker} \cdot PC_{worker}}{P_{produced}}$$

n^j_{worker}	number of required workers [-]
PC_{worker}	personnel costs [€/h]
	here: 40.00 €/h (Basic)

$$C^j_{footprint} = \frac{A^j_{footprint} \cdot AC_{building}}{P_{produced}}$$

$A^j_{footprint}$	area of machine footprint [m²]
$AC_{building}$	area unit cost [€/m²/h]
	here: 0.008 €/m²/h

$$C_{Building} = \frac{\left(A_{building} - \sum_{j=1}^{n} A^j_{footprint}\right) \cdot AC_{building}}{P_{produced}}$$

$A_{building}$	area of entire building [m²]
	here: 5200 m²

$$C_{dry\ room} = \frac{IC^{dry\ room}}{t_{depreciation} \cdot P_{produced}} + \frac{E^{dry\ room}_{electric} \cdot CC_{electric}}{P_{produced}} + \frac{E^{dryroom}_{gas} \cdot CC_{gas}}{P_{produced}}$$

$$C_{overhead} = \sum_{j=1}^{n} C^j_{labor} \cdot i_{overhead}$$

$i_{overhead}$	overhead rate [-]
	here i=0.6

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