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Forecasting Battery Cell Production in Europe: A Risk Assessment Model

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Abstract: The increase in battery demand, particularly from the mobility sector, has resulted in a significant increase in the required production capacities. Europe is facing a large-scale expansion of production capacities. Currently, the battery cell demand in the region accounts for approximately 25% of global demand, while only 10% of global production capacities are located there. This has motivated the announcement of a large number of production projects of over 2 TWh by 2030, which would mean overcapacity compared to projected European cell demand. In recent years, however, many of the announced Gigafactories have been delayed or cancelled. This paper aims to develop a risk assessment model for forecasting realistic future capacities for battery cell production in Europe. The proposed model combines an evaluation of industry announcements at the project level with a Monte Carlo simulation to translate the announced production projects into a European production capacity forecast. Therefore, the likelihood of implementation for individual projects is analysed within 11 topics (company, country and maturity related) and scenarios for future European production capacities are elaborated. Model validation indicates that from 54% to 75% of the announced capacities in Europe are likely to be realised (approx. 1.2 GWh–1.7 GWh by 2030). The majority of battery production projects announced in Europe are still in the planning phase (66%) with Germany, France, Scandinavia and Eastern Europe emerging as key regions. The modelling of production capacities predicts that dependency on cell imports to Europe will be reduced compared to today.

Keywords: battery production; lithium-ion battery; European battery industry; modelling; risk assessment

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1. Introduction

Global announcements for production capacities for LIB cells surpass 14 TWh by 2030. According to the industry's announcements, the growth rates in Europe will exceed those in Asia and the share of production capacity in Asia (85% in 2023) will fall to around 40% of the global production capacity in 2030, while the share in Europe will increase from around 10% to up to 20% [1]. Many failed construction projects may lead to uncertainties about future capacity expansion [2], but a significant amount of capacity has still been announced in Europe.

In particular, the growing relevance of technological sovereignty and a corresponding move away from the dependence on China's imports reinforces the motivation for a European battery production [3,4]. European companies with large battery cell demand, such as automotive OEMs, are increasingly pursuing their own battery cell production in order to achieve reliability of battery supply. Furthermore, the emerging European market enables the establishment of foreign cell manufacturers and start-ups. Next to cell producers entering the market, upstream material manufacturers or the mechanical engineering industry can also profit from the emerging battery cell industry. This results in a dynamic expansion of production capacities in Europe.

The announced global production capacities however significantly exceed the forecasted demand of around 2–6 TWh [5–14]. As a result, not all of the production projects in the pipeline are likely to be realised. The past has shown that many announced production capacities are not realised as originally planned. This may be, for example, due to company insolvencies [15,16], a market that has developed less dynamically than expected [17,18] or more favourable production costs at alternative locations [19]. In Europe, 11 projects in giga scale have failed in the recent past, and for a further nine, the start of operation or expansion to the originally planned production is uncertain or delayed. It is not possible to predict which players will be able to establish themselves on the market in the long term.

1.1. Toward a Forecast Model for Cell Production Capacities

There are announcements for the build-up of more than 2.2 TWh annual production capacities in Europe until 2030. These far exceed the expected demand for cells in Europe [20]. A consolidation of the market can therefore also be expected in Europe.

This paper aims to help paint a more likely picture of the industry's development, taking into account the most important risk factors and their impact on the likelihood of implementation for future production projects. We propose a model combining an evaluation of industry announcements on project level with a Monte Carlo simulation. This makes it possible to assess the likelihood of implementation of individual projects and to develop scenarios for future European production capacity. So far, there are very few scientific methods to forecast this industry. While a large number of analysts make various statements about future production capacities [9,12,21–27], the underlying methods are usually unclear. Scientific market analyses often focus on the demand side (e.g., bass diffusion [28]), while the production ramp-up is rarely considered using scientific-based research methodologies. We are only aware of one approach that also takes into account more than one factor to determine the likelihood of implementation of individual battery production projects [29]. In other industries, there are individual studies addressing the production ramp-up (e.g., hydrogen [30] or car production [31]).

The added value of our approach is twofold: First, the comparability that results from the systematic parameterisation of production projects. A state that cannot be taken for granted in view of the very inhomogeneous data situation and the way in which players communicate their production plans. Second, we deliberately use the uncertainties inherent in all forecast models to create a range of scenarios for future European production. The approach is designed to be transferable to other regions.

1.2. Challenges for European Production Projects

In addition to global overcapacities, which represent a general challenge for the industry, locations and players are competing on very specific factors. These include, for example, energy, wage and investment costs, but also production experience or access to suppliers and customers.

As cell production has a high electricity consumption [11], the influence of the industrial electricity price is of great importance. The ups and downs of electricity prices in Europe therefore have an influence on the subsequent cell costs. The intra-European variance of the electricity price of, e.g., Norway and Germany (0.164 USD/kWh vs. 0.348 USD/kWh, as of March 2024 [32]) translates to a different attractiveness of the respective locations within the region.

Industry subsidies are another factor that influences the realisation of cell production, sometimes in a disruptive way. Delays announced in 2023 and 2024 for projects of Tesla [19], Freyr [33] and Northvolt [34] in Europe can be attributed to the Inflation Reduction Act (IRA) in the USA. The subsidies provided in the IRA are as high as 35 USD/kWh [35]. Such subsidies and other far-reaching subsidies from other countries have an impact on the prioritisation and, the final implementation of individual projects.

Despite the existing challenges in Europe, there is a clear trend towards local cell production. This can be seen from the industrial activities that have been announced and already implemented. Due to the growing political will to reduce geopolitical dependencies and the advantages of short supply chains, Europe can increasingly establish itself as a location for cell production in the future. A well-developed and well-funded R&D sector for both state-of-the-art LIB technologies [36] and potential follow-up technologies such as sodium-ion batteries (SIB) [37] have a positive influence on this trend. An important political impulse for supporting the European battery production is also a new battery regulation [38]. Among other things, it regulates the traceability of the CO_2 footprint, the disclosure of supply chains and the proportion of recyclates to be used in new batteries. This opens up competitive advantages for cells manufactured in Europe. However, the minimum amount of recyclate (from end-of-life batteries or production waste) in future batteries also limits the possible production capacity.

2. Materials and Methods

The procedure for modelling future cell production capacity in Europe is divided into several conceptual and operational steps (Figure 1). In the concept phase, topics describing the respective projects and their environment were developed. In addition, evaluation categories for the 11 topics were introduced. The significance of each of the topics and the corresponding evaluation categories for the probability of implementation of production projects was determined through expert interviews.

In the implementation phase, various data sources were used to identify production projects and classify them in the evaluation categories of the different topics. Scenarios for potential production capacity in Europe were developed using a Monte Carlo simulation.

A total of 11 different topics are used to determine the risks associated with each announcement that could lead to the failure of the planned project. Every production project was individually categorised to the evaluation category for every topic (see Section 2.3). There are either two or three evaluation categories per topic. This made it possible to calculate an overall likelihood of implementation per project (see Section 2.5). By varying the individual likelihoods of implementation using minimum and maximum values, different scenarios can be calculated at the end (see Section 2.6). This was also carried out due to the fact that individual probability values are difficult to predict exactly.

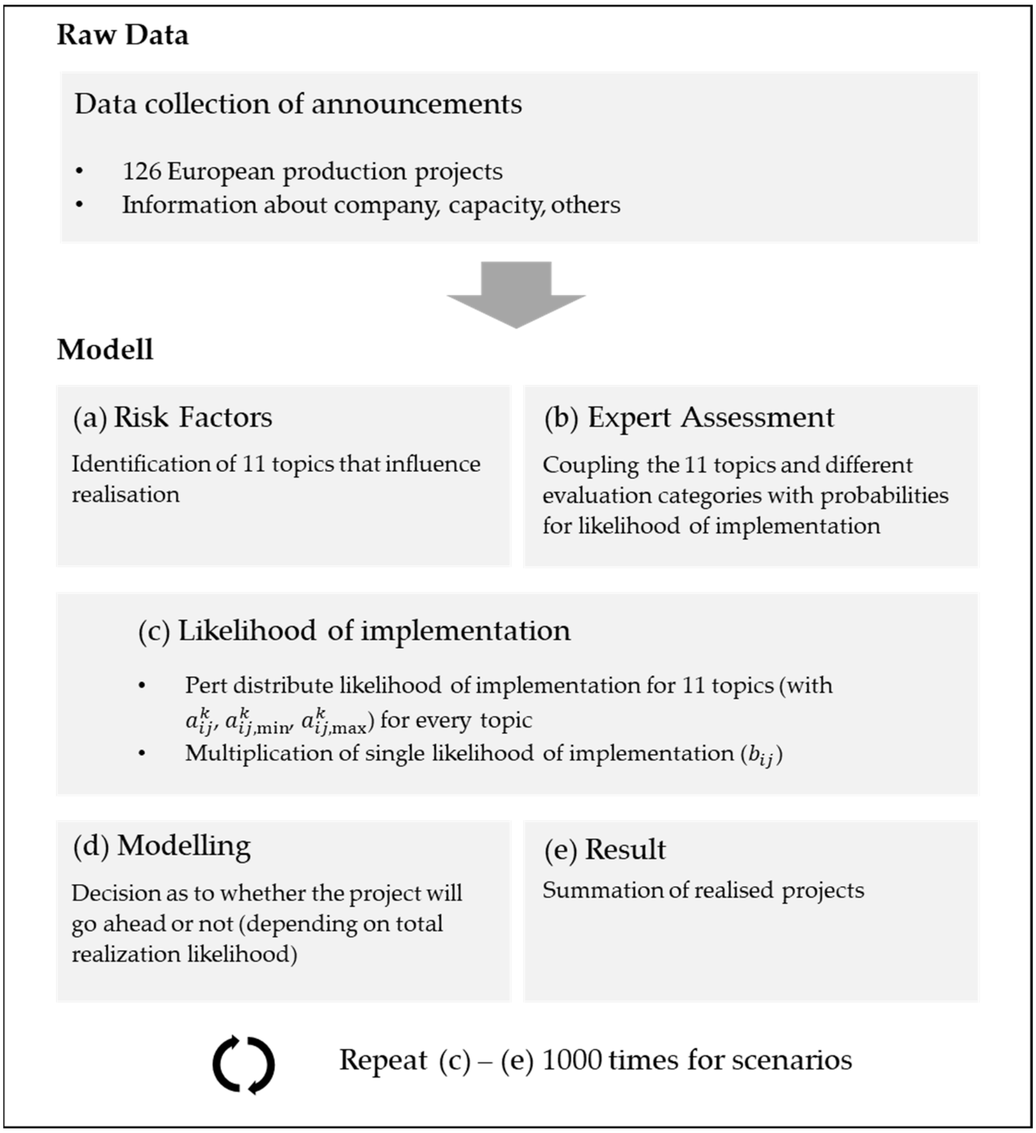

Figure 1. Overview of the methodology used in this study.

2.1. Data Base of Battery Production Projects

The Fraunhofer ISI in-house cell production database contains over 650 entries of existing or announced battery cell manufacturing plants or expansion stages with relevant production capacities worldwide. A total of 126 of those projects are based in Europe and are considered for this paper (data as of November 2024). The database aggregates information on location (country) and capacity (GWh/a) as well as produced cell chemistry of industrial LIB production sites as communicated by cell producers. The data are based on market studies, producer press releases or news articles. Particularly intensive use was made of electrive [39], SNE Research [40], insideevs [41] and Argus Media [42]. The database was set up in 2017 and is being updated constantly. Each piece of information about potentially planned production sites, either by the cell manufacturer or third sources, qualifies as an announcement, if at least the cell manufacturer or the production site on a communal level is specified.

2.2. Definition

Several parameters were used for the model. Projects and evaluation topics are indicated by indices. Table 1 contains all the variables and indices used in the model, which are introduced in the next sections.

Table 1. Overview of parameters used for model the future cell capacity.

Term	Definition
k, superscript	Superscript index for 11 topics describing the status of each production site.
l, superscript	Superscript index for different evaluation categories the production sites are classified into. There are either two or three evaluation categories per topic.
i, subscript	Subscript index production site.
j, subscript	Subscript index for different expansion stages (e.g., 1st line, 2nd line) of one project.
p^{kl}	Expert-based averaged independent likelihood of implementation for each evaluation category along the 11 topics. Values lower or equal than 1 (1 = no risk, 0 = no likelihood of implementation).
Δp^{kl}	Standard deviation of p^{kl} taken from the spread of expert assessments.
$p^{kl}_{\min}$, $p^{kl}_{\max}$	$p^{kl} \pm \Delta p^{kl}$
a^k_{ij}	Evaluation value into which project i, j was classified.
$a^k_{ij,\min}$, $a^k_{ij,\max}$	Minimum and maximum value for the evaluation category of an individual announcement.
a'^k_{ij}	PERT distributed evaluation category of an individual announcement.
b_{ij}	Final likelihood of implementation for each production site i and expansion stage j.

In the following, we will describe each announced production site by the subscript i. As some announcements are split over several production stages, a second subscript j is introduced to specify the corresponding stage. Evaluation values (likelihood of implementation) for the different topics a^k are therefore individually defined for each location with a^k_{ij}.

2.3. Factors Describing the Likelihood of Implementation

The 11 topics include four different topics to classify the reliability of the company behind the project. Additionally, there are three topics that describe the frame conditions found in the production countries. Three further topics are introduced, characterising the production announcement itself. An overview is provided in Table 2.

Table 2. Evaluation categories of risk factors.

Topic	Categories and Classification
Construction Status ($k = 0$)	(1) Planning phase (2) Construction phase (3) Finished
Company Credibility ($k = 1$)	(1) SMES (<250 employees and <EUR 50 million in sales (or a balance sheet smaller than EUR 43 million) (2) Large company (3) Company group
Battery Credibility ($k = 2$)	(1) New in business (2) Small scale producer (<1 gwh) (3) Production on giga scale (>1 gwh)
Financial Credibility ($k = 3$)	(1) Financial difficulties (2) No financing detail is given (3) Valid financing (or company group, see $k = 1$) due to investment rounds
Offtake ($k = 4$)	(1) No details (2) Supply contract (public announced), OEM invest or internal cell demand

Table 2. *Cont.*

Topic	Categories and Classification
Energy Price ($k = 5$)	(1) >+10% of IEA median for electricity price in Europe (2) Within ±10% of IEA median for electricity price in Europe (3) <−10% of IEA median for electricity price in Europe
Labour Cost ($k = 6$)	(1) >+10% of OECD median for average wages in Europe (2) Within ±10% of OECD median for average wages in Europe (3) <−10% of OECD median for average wages in Europe
Subsidies and Policies ($k = 7$)	(1) No existing subsidy structures or other indirect support measure (2) Existing subsidy programs or other indirect support measure
Material Supply ($k = 8$)	(1) Not specified (2) Material resources in country or supply contracts
Location Detail ($k = 9$)	(1) Not specified (2) Information about the production site (region or town)
Planning Detail ($k = 10$)	(1) Unclear announcement with only weak data robustness or reliability of the source (2) Optional location or extension on demand (3) Clear announcement with good data robustness and reliability of the source for a planned production site that is not optional or an extension on demand

Construction Status ($k = 0$): The likelihood of implementation of a production location correlates with the status of the construction progress. The more advanced the construction project is, the more likely it is to be finalised. There are three evaluation categories, (1) the planning phase, (2) the construction phase after the first building work has started and (3) the status when the building project is completed.

Company Credibility ($k = 1$): We used the company size in terms of turnover and number of employees to define the Company Credibility. The first evaluation category (1) consists of SMEs [43]. The second evaluation category (2) is for large companies and the third category (3) is for company group (e.g., characterised according to German stock corporation law [44] by at least two individual companies under joint management).

Battery Credibility ($k = 2$): The Battery Credibility is intended to account for experience in the production of cells on industrial scale. The experience already gained in battery production is an important indicator in estimating the probability of successfully implementing new production facilities. It helps with a better access to offtakers and companies gain a higher level of trust from investors. Particularly in the early stages, it also has an impact on production quality and the corresponding scrap rate during ramp-up. The first evaluation category (1) applies to companies that do not have any cell production facilities. In the second evaluation category (2) are companies that have so far manufactured batteries on a small scale with a production capacity of less than 1 GWh per year. In addition, there is a third evaluation category (3) with cell manufacturers who already achieved Giga-scale production with high yield (>1 GWh production capacity per year).

Financial Credibility ($k = 3$): The Financial Credibility quantitatively reflects whether the company is likely to secure financing for the investment in projects either through its size or through financing rounds made public. If one of those conditions is true, the company is assigned to the third evaluation category (3). Company groups are assigned to this category by default, as long as there is no other information. It can be assumed that they have a certain financial strength due to their size. If there is no explicit financial information, the second evaluation category (2) can be assigned. If there are reports of financial difficulties, including insolvency, only the first evaluation category (1) is applied here.

Offtake (k = 4*)*: Describes the existence of offtake agreements and investments from OEM, either to external customers or in-house (e.g., OEM own production). A two-point scale categorizes whether (1) there is no information on offtake agreements and investments by an OEM or (2) there is an offtake agreement. Automotive OEMs that set up their own cell production are in the second category by default.

Energy Price (k = 5*)*: Due to the fact that energy costs make up a relevant proportion of the total costs for cell production [45], the corresponding electricity costs in the country where the gigafactory is to be built are important for its establishment. Country energy costs for the industry are compared to the average value of an IEA median [46]. By using the IEA mean value, a reference was used that represents the majority of the most important industrialised nations (and thus also countries in which cell production could take place). It must be mentioned that China, as the most important cell manufacturer, is not represented in the used IEA database and was added manually [47]. The energy price has a three-point scale for the evaluation categories: (1) either the electricity price is higher than the IEA median (>10%), (2) the electricity price is within the range of the median (±10%) or (3) the electricity is significantly cheaper than the IEA median (<10%).

Labour Cost (k = 6*)*: In addition to the cost of electricity, labour costs also have an influence on the total cost of the cell and thus on the likelihood of implementation when selecting a possible location for a new cell factory. Similar to the energy price, a three-part categorisation is used here to compare average wage costs with those of the individual countries. For the categorisation, we used OECD labour costs [48]. Here, too, the country data were determined against the median value: (1) either the labour costs are significantly higher than the OECD median (>10%), (2) the labour costs are within the range of the median (±10%) or (3) the labour costs are cheaper than the OECD median (<10%).

Subsidies and Policies (k = 7*)*: Subsidies in various forms (e.g., tax breaks, loans, public investments or favourable energy prices) as well as applicable political regulations, such as quotas of inland production for certain value chain steps or the European battery regulation [38], which includes requirements for the manufacture process of the batteries placed on the market, can also tip the scale in favour of a cell production location. The subsidies and policies topic indicates whether any subsidies or other political support programs are provided in a potential production country (2) or if there are no measures (1). Sometimes it is difficult to clearly identify a funding measure, as it does not always come from clearly identifiable sources, e.g., public grants, but can also be provided indirectly (e.g., through market incentives).

Material Supply (k = 8*)*: The Material Supply addresses whether or not battery raw materials are mined or refined in the country of the project. Also, the production of battery materials (active materials, separator and electrolyte) is taken into account. Additionally, it is considered whether the companies have publicly disclosed supply contracts with raw material suppliers or material producers. The topic has a two-part scale. If there is information about an existing material supply strategy, the announcement is assigned the second evaluation category (2). If there is no information, the value is assigned to the first category (1).

Location Detail (k = 9*)*: When new announcements are made, there are usually varying degrees of details regarding the production location. In some cases, production facilities are simply announced without a geographical location (1). However, there are also more concrete announcements with the naming of regions or already defined cities (2). This is assumed to correlate with the concreteness of the plans and, therefore, again to the likelihood of realisation.

Planning Detail (k = 10*)*: The topic of Planning Detail is introduced in order to specify the quality of the information available and to assess whether the project schedules are realistic. The realisation of the project is considered doubtful if no recent information about the production location (at least on a country level) and the time schedule (at least a year for start of production or construction) is given. The information is considered recent, if it is younger than two years and the next expected milestone (start of construction or start of production) is not overdue for longer than one year. In this case, the project is assigned to the third evaluation category (3). The second category (2) is reached if the announcement is recent but only as an expansion depending on the battery demand or an optional site. If there is no recent information or the first reports about a termination of the production site are publicly discussed, the project is classified with the first evaluation category (1).

2.4. Expert Interviews on Independent Risk Factors

The individual likelihood of implementation (p^{kl}) associated with each risk factor (topics), indexed by k, and the possible evaluation categories (indexed by l) were surveyed and discussed in expert interviews. The interviews were conducted in the first half of 2024 with a total of eight experts from research and industry. The experts selected ensure a combination of perspectives on the emerging battery industry in Europe, which reduces the risk of introducing systematic biases at this step of the analysis. From the industry, an R&D manager at a large European cell manufacturer, a manager at an industry association, an expert at a European manufacturer of commercial electric vehicles and a battery market and technology consultant were interviewed. From the research perspective, two senior battery researchers at a European RTO, a battery process engineer at a European RTO and a production expert at a European battery cell pilot line were interviewed. For each of the 11 predefined topics, the interviewees were asked how important they generally consider the respective topic to be for the probability of implementation. They then had to give each of the evaluation categories of the 11 topics a value for the associated probability of implementation. The implementation probabilities of the 11 topics were to be regarded as independent, i.e., for the evaluation of an individual topic, the experts were to assume that the production project would achieve the best evaluation category in all other topics. The procedure is shown as an example for the topic *Battery Credibility* in Table 3.

Table 3. Procedure for interviewing experts and evaluating individual implementation probabilities on the example of topic *Battery Credibility*.

	Evaluation Category 1	**Evaluation Category 2**	**Evaluation Category 3**
	Announcement by a company that does not have any cell production facilities	Announcement by a company that already runs a smaller production facility <1 GWh per year	Announcement by a company that already runs a Giga-scale production facility
Interview question	How high would you rate the likelihood of implementation in this category compared to category 3?	How high would you rate the likelihood of implementation in this category compared to category 3?	Assume that this category is associated with a 100% likelihood of implementation.
Answer option	≤100%	≤100%	

The probability determined by the experts has a significant impact on the end result (see sensitivity analysis in the Supplementary Materials). In order to also reflect this uncertainty in the modelling, the mean value p^{kl} for the implementation probabilities was determined from the responses of all experts. The values $p^{kl}_{\min} = p^{kl} - \Delta p^{kl}$ and $p^{kl}_{\max} = p^{kl} + \Delta p^{kl}$ were determined from the standard deviation Δp^{kl} of p^{kl} (eight expert responses), with $p^{kl}_{\max} \leq 100\%$ and $p^{kl}_{\min} \geq 0\%$ as the limit.

The triple p^{kl}, $p^{kl}_{\min}$ and $p^{kl}_{\max}$ therefore reflects the implementation probability associated with the respective evaluation category, but also the uncertainty due to the expert evaluation. It was precisely this uncertainty in the methodological approach that was used to evaluate the bandwidths of future production potential in Europe. The highest category of every topic is excluded from the expert rating and always receives a value of $p^{kl} = 100\%$, so that there is no reduction in the likelihood of implementation for ideal conditions of the respective topics.

2.5. Likelihood of Implementation of Production Projects

The likelihood of implementation of the individual projects (indexed by i, j) associated with each topic (indexed by k) results from the category l assigned to them, so that the following applies:

$$a^k_{ij} = p^{kl} \text{for the } l \text{selected for } i, j, k \tag{1}$$

The same applies to $a^k_{ij,\min}$ and $a^k_{ij,\max}$ ($a^k_{ij,\min} = p^{kl}_{\min}$, $a^k_{ij,\max} = p^{kl}_{\max}$). For the highest categories of every topic, $a^k_{ij} = 100\%$. Unlike in the expert survey, however, the topics are not independent of each other. The interdependencies must be taken into account when determining the a^k_{ij} (see next section).

2.5.1. Interdependencies Between Different Topics

There are dependencies between evaluation categories of different topics for an individual project, so that the total likelihood of implementation does not simply result from the multiplication of the corresponding values of p^{kl}. Instead, there are individual exceptions, for example, most topics such as *Location Detail* or *Company Credibility* no longer play a role as soon as the production project has been set up (*Construction Status* is finished). Table 4 provides an overview of the impact for the different construction stages regarding other topics. As soon as topics are no longer considered, they are assigned the likelihood of implementation $a^k_{ij} = 100\%$.

Table 4. Overview of interdependencies between the topics for risk assessment.

If	Then
As soon as *Construction Status* ($k = 0$) is finished ($l = 3$)	*Company Credibility*, *Battery Credibility*, *Energy Price*, *Labour Cost*, *Subsidies and Policies*, *Location Detail* and *Planning Detail* no longer matter $a^k_{ij} = a^k_{ij,\min} = a^k_{ij,\max} = 100\%$ for $k \in \{1, 2, 5, 6, 7, 9, 10\}$
As soon as *Construction Status* ($k = 0$) is under construction ($l = 2$)	*Location Detail* is defined and *Planning Detail* obvious $a^k_{ij} = a^k_{ij,\min} = a^k_{ij,\max} = 100\%$ for $k \in \{9, 10\}$
If a company ($k = 1$) is defined as concern ($l = 3$)	It is assumed that the financial situation is solid ($a^3_{ij} = a^3_{ij,\min} = a^3_{ij,\max} = 100\%$)
If energy costs obtain subsidies $k = 7, l = 2$—explicit energy subsidies)	The likelihood of implementation related to local energy cost is adjusted ($a^5_{ij} = a^5_{ij,\min} = a^5_{ij,\max} = 100\%$)

In a subsequent step, these dependencies were taken into account and the corrected likelihood of implementation factors a^k_{ij} are calculated.

2.5.2. Overall Probability

The likelihood of implementation b_{ij} for a project (indexed by i, j) is the product of a_{ij}^k:

$$b_{ij} = \prod_{k=0}^{10} \left(a_{ij}^k \right) . \tag{2}$$

2.6. Statistical Evaluation and Forecast Model

For the scenario-based evaluation, a Monte Carlo simulation is conducted. Instead of assuming fixed values for a_{ij}^k, a function is used to randomly draw the respective likelihood of implementation values within the defined ranges according to the PERT distribution [49]

$$a{\prime}_{ij}^{k} = f_{\text{PERT}}\left(x_{\text{rand}}, a_{ij}^k, a_{ij,\min}^k, a_{ij,\max}^k \right) \frac{1}{B(\alpha, \beta)} x_{\text{rand}}^{\alpha-1} (1 - x_{\text{rand}})^{\beta-1} + a_{ij,\min}^k, \tag{3}$$

by taking x_{rand} randomly from a uniform distribution on the interval $[0, 1]$. The beta function is defined as

$$B(\alpha, \beta) = \int_0^1 t^{\alpha-1} (1 - t)^{\beta-1} \mathrm{d}t, \tag{4}$$

with the substitutions

$$\alpha = 1 + 4 \cdot (a_{ij}^k - a_{ij,\min}^k \Big) / \left(a_{ij,\max}^k - a_{ij,\min}^k \right), \tag{5}$$

$$\beta = 1 + 4 \cdot (a_{ij,\max}^k - a_{ij}^k \Big) / \left(a_{ij,\max}^k - a_{ij,\min}^k \right). \tag{6}$$

PERT distributions are commonly used to account for uncertainty in experts' assessments, as it takes into account edge parameters that can be assessed more easily [50]. The PERT distributed likelihood of implementation is given as $a\prime$ instead of a. Finally, the overall likelihood of implementation $b\prime$ is calculated according to Equation (2), which is then used to model which announcements are realised.

For announced expansions of production facilities (on top of existing future facilities), only those construction projects are taken into account for which the previous projects (existing future facilities) have also been successfully realised.

For scenario calculations, the PERT modelling steps were repeated 1000 times. Through the repetition, the median value was determined (trend value) and a minimum (10% quantile) and a maximum (90% quantile) was calculated. The model is implemented using Python. We ran all calculations on a standard Lenovo notebook with i7-8565U @1.8 GHz and 16 GB RAM (Lenovo, Beijing, China).

2.7. Data Collection for Risk Factors and Data Completeness

The data used to classify the various production projects into evaluation categories along 11 topics were obtained from a variety of sources. Information such as size, period of activity in the battery industry, information of financial details or supply relationships of the company was collected by desk research, e.g., from company websites. Country-specific information on energy costs in different EU countries has been taken from Eurostat and the IEA [46,51] labour costs from the OECD database [48]. Additional desk research was used in the event of data gaps for energy or labour costs as well as for the collection of information about subsidies or the availability of raw materials. For both, energy and labour costs for the base year are 2023. For the energy costs, we have limited ourselves to the cost of electricity.

There are two fundamental risks with data collection in terms of completeness or accuracy: (1) production projects could be completely overlooked because they are not publicly communicated and (2) projects might be categorised in the wrong category because up-to-date data are not available. In the past, manufacturers have linked the setting up of production projects with strong PR communication, probably because battery cell production is perceived as a future field and as politically and socially desirable. The reasons for a covert build-up of production projects in Europe are not known, so we estimate the probability of overlooking entire projects (1) as very low. In addition, the existing database was compared with several publications [2,27,29,52] and consolidated so that it can be assumed that all construction projects were recorded on a giga scale.

Particularly with regard to the dynamic topics that affect the project itself (e.g., *Construction Status* $k = 0$ or *Offtake* $k = 4$), the timeliness of communication plays a very important role (2). When offtake agreements are concluded, for example, it cannot be assumed that these will always be communicated to the public promptly. This results in the risk of inaccurate or outdated categorisation of projects

3. Results

3.1. Results of the Expert Assessment of the Eleven Topics

The experts assessed the likelihood of implementation for a total of 11 topics and 29 categories. All results of the expert survey are presented in the Supplementary Materials.

To simplify results and demonstrate the varying impact of the 11 topics on the likelihood of implementation, we have assigned them to the impact categories high, medium and low (H/M/L) in Table 5. A high impact corresponds to a mean likelihood of implementation below 70% as assigned by the experts. A low impact corresponds to likelihood of implementation of over 90% in the first category.

Table 5. Overall impact (low/medium/high) and likelihood of implementation of the individual topics and evaluation categories.

Topic	0	1	2	3	4	5	6	7	8	9	10
Overall impact (L/M/H)	L	M	H	H	L	M	L	M	L	H	H
Likelihood of implementation (category 1) in percent	95	80	70	25 *	90	80	90	85	95	70	60
Likelihood of implementation (category 2) in percent	99	90	90	95 **	100	98	99	100	100	100	85
Likelihood of implementation (category 3) in percent	100	100	100	100		100	100				100

* Due to the dependency with *Construction Status* also 30% ($k = 0, l = 2$) or 50% ($k = 0, l = 3$). ** Due to the dependency with *Construction Status* also 100% ($k = 0, l = 3$).

According to experts, *Financial Credibility* in particular has a major influence on the final likelihood of implementation of a project. Financial difficulties are an enormous problem for the cost-intensive realisation of a cell factory. Also important is the *Location Detail* because announcements were often made regarding one or more new production facilities but then not pursued further. This is followed by the *Battery Credibility*. The ability to already produce batteries is particularly helpful in the ramp-up phase and can also be an advantage in the planning phase of the project. Fixed capacity planning taken up in the *Planning Type* versus an optional expansion must also be backed up with corresponding probabilities. Therefore, this topic is as relevant as the *Battery Credibility*.

Material Supply on the other side is not very impactful in this analysis, as it is often very difficult to evaluate the supply chain of individual companies from an external perspective. For this reason, little weight has been assigned to this aspect. The same applies to *Offtake*. As labour costs, for example, account for less of the manufacturing costs than energy costs [45], the ratio must also be represented in the probabilities. A table of the individual values for every evaluation category can be found in the Supplementary Materials.

If the standard deviations from the expert survey are compared with each other, it is noticeable that the standard deviation is the highest for evaluation category with the lowest likelihood of implementation. For example, Topic 3 (*Financial Credibility*) and Topic 10 (*Planning Type*) have higher deviations. Although Topic 4 (*Offtake*) has slightly lower influence of the later realisation, opinions on the influence also differed somewhat here. A table with all the standard deviations (and thus the basis for the min and max values) can be found in the Supplementary Materials as well.

3.2. Results of the Categorisation of Production Projects

Adding up all cell production projects announced in Europe until 2030 results in a final cumulative production capacity of 2.2 TWh per year. However, the actual production capacity is expected to be significantly smaller due to failure of some projects.

Scandinavia, Germany and France are still in the process of building up capacity. By 2030, a total of around 600 GWh and approx. 170 GWh have been announced in Germany and France alone, while in Scandinavia, for example, the figures are each more than 100 GWh in Norway, Sweden and Finland. But also in Eastern Europe, further battery production capacities are announced (e.g., in total approx. 120 GWh in Poland and roughly 250 GWh in Hungary).

As shown in Figure 2, the majority of projects (66%) are in the planning phase, while only a small proportion are currently under construction (13%) and around one in five plants (21%) is already up and running. The clear majority of the announcements come from companies with a group structure (79%) and all of the remaining announcements are from small- and medium-sized companies (21%). The ratio is similar with respect to the cell capacity announced for 2030 (91% announced by large companies and groups).

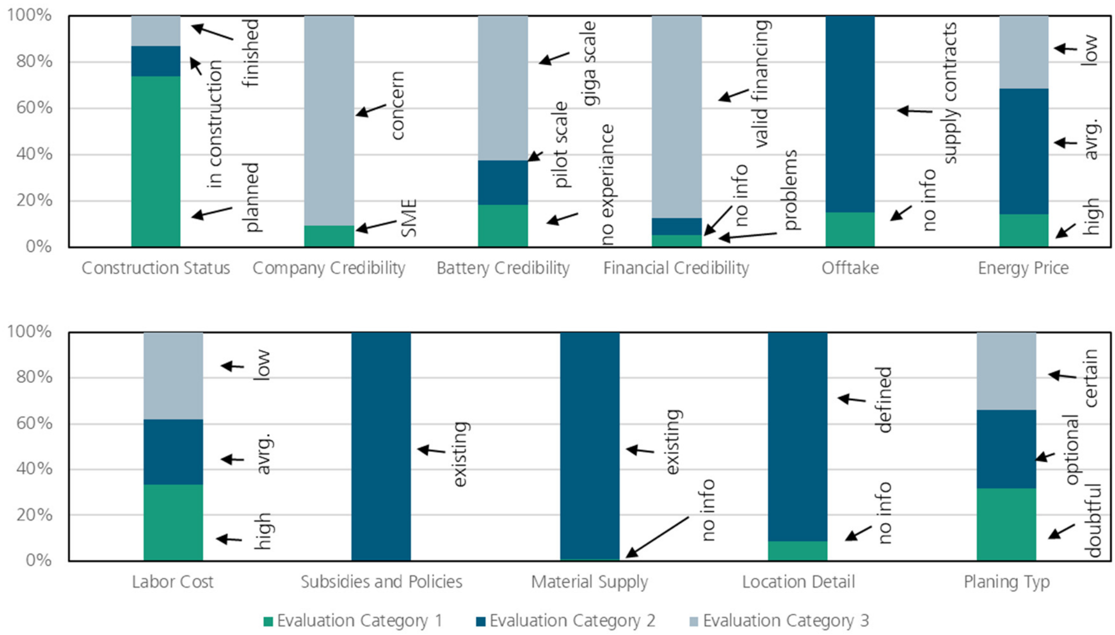

Figure 2. Capacity weighted share of production capacities in the respective evaluation categories of 126 projects.

A small part of companies has no experience in the larger scale production of batteries (22% of the announcements and 18% of the capacity). However, the companies often already produce in smaller pilot plants (33%/19%) or already operate other gigafactories (45%/62%). Financially, most of the announcements are on a supposedly secure footing (79%/87%).

The list of companies with cancelled announcements became longer, especially in 2024. Examples for factories cancelled are the following: in Europe, projects by ABEE, AMTE, Blackstone Technology, Britishvolt (later Recharge Industry), Farasis, Italovolt, Northvolt, SVOLT and PowerCo have definitely been cancelled [53–59]. As this is already known, such announcements are no longer listed in the database.

The trend is that most of the projects have a designated supplier contract or own cell demand (76%/85%).

When analysing the production location, it is noticeable that most of the production capacity is in countries with low (31%) or average (54%) electricity costs. Only 14% are in high-energy-cost countries (e.g., UK or Slovakia). Energy costs are playing an important role within Europe [60]. Germany, for example, moves from the lowest evaluation category to the middle evaluation category, after 2021, when energy prices were still very high due to the start of the Ukraine war. France and Italy have seen a sharp increase in industrial electricity prices the last years. This resulted in lower evaluation categories. [46].

The data suggest that labour cost did not play any role for the selection of production locations (evenly distributed among the three categories). Just under 38% of the announced capacities are in countries with low wage costs and 29% in average wage regions (vs. 33% in high-wage countries). All announced production capacities in Europe are located in countries with the option to apply for subsidy programs (e.g., IPCEI in the EU and Finland and comparable programs in further countries, such as the UK).

The proportion of announcements with access to critical materials for battery cell production is also very high. Since battery raw materials are now produced in more than half of all European countries and the announced gigafactories are concentrated in these regions, almost all announced cell factories could draw on regional materials. In addition, most of the major manufacturers have already signed supply contracts with material manufacturers.

No specification of a project location (town) is yet known for 21 of the 83 announcements in the planning phase. These are mostly announcements that are planned to be built towards the end of the decade. Approximately 32% of the capacity announced for 2030 is considered doubtful based on the available information. Around two-thirds are firmly planned capacities (34%) or optional stages (34%).

The overall likelihood of implementation (multiplication of individual likelihood of implementations for the 11 topics) ranges from 9% to 96% for not yet finished projects, thus covering almost the entire spectrum of possible probabilities.

The total number of projects that have reached the status "finished" is 27. Together, they have a maximum capacity of almost 300 GWh when reaching their full capacities and are considered operational in all possible simulation outcomes. Asian manufacturers have an average likelihood of implementation value of 83% for European battery production projects (weighted according to their announced production capacity). European manufacturers, on the other hand, are at 54%. The same likelihood of implementation applies to American manufacturers (56%). The total average for the likelihood of implementation of the 126 announcements is at 66%.

3.3. Scenarios for Future Production Capacities in Europe

The possible scenarios for future theoretical production capacity for batteries in Europe were determined using 1000 Monte Carlo simulations. The scenario range for 2030 is between 1.2 and 1.7 TWh (Figure 3a). This means that between 25 and 46% of the announced production capacity is not expected to be realised.

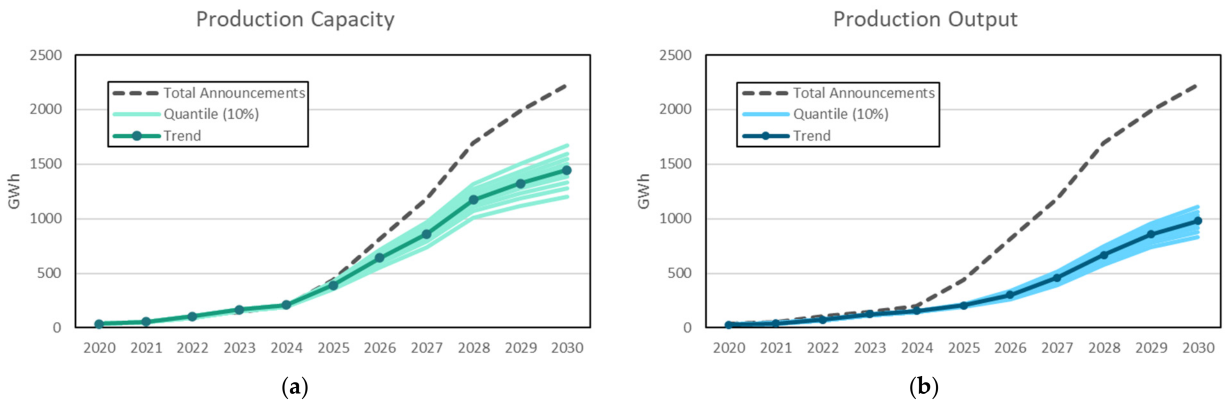

Figure 3. (**a**) Announced, theoretical as well as (**b**) announced and actual battery production capacity scenarios in Europe. The bright lines give the quantiles in steps of 10%.

The scenario range is influenced by two factors. Firstly, the standard deviation of the expert judgements with the corresponding minimum and maximum values for $a^k_{i,j}$ are calculated. Afterwards, a new Pert distribution of the likelihood of implementation for each number of repetitions causes variances in the results. Additionally, this is reinforced by the random decision used as to whether a project is realised or not.

Statistically, the projects that have a likelihood of implementation of approx. 50% play a particular role in the scenario development, as these are either realised or not in a repetition. A stronger division into projects with high- and low-probability values would make the forecast more precise. Figure 4 shows that the distribution of the project likelihood of implementation is, however, quite linear.

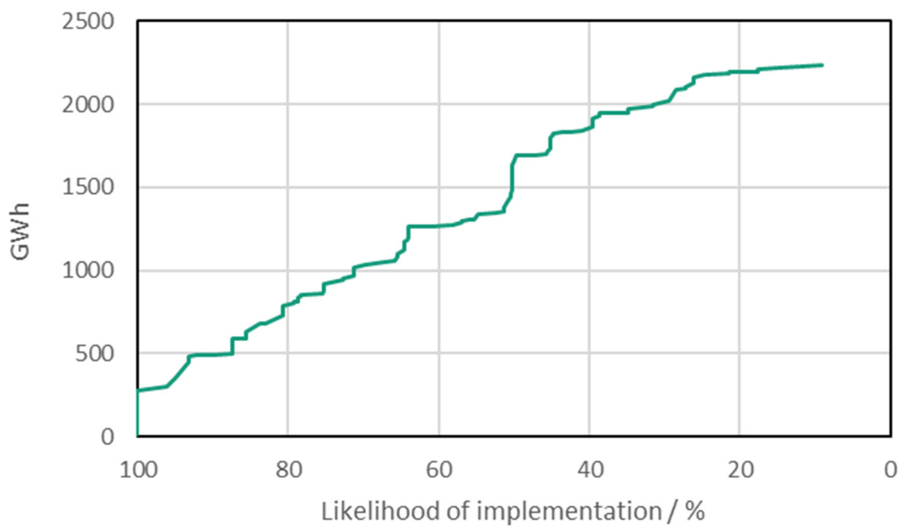

Figure 4. Likelihood of implementation applied over the announced production capacity in Europe.

3.4. Regional Hotspots in European Battery Production

In Europe, several regions are emerging as attractive for battery production due to different arguments and individual USPs. While Eastern Europe, for example, can offer attractive labour costs and lower energy costs, cell production in Scandinavia might be particularly sustainable due to the high proportion of renewable energies. In Germany and France, there is high cell demand due to the local automotive industry.

In the past, production costs were a highly decisive factor in the choice of location. This reason played a significant role for locating the so-far largest cell production capacities in Europe in Hungary (SDI, SK On) and Poland (LGES). In these countries, labour costs are somewhat lower, while energy costs are particularly low by European standards.

If we look at the nationwide evaluation of the production capacities, there are also clear differences in the average likelihood of implementation in relation to production capacities. Projects located in Poland have a high average likelihood of implementation of 99%, followed by Hungary with an average value of 82%, partly due to the existing plants and the extensive experience in battery production of players located there. The likelihood of implementation is lowest for projects in Latvia (18%) There is only one project in the country, so the likelihood of realisation is not related to the country factors but to the actor. The comparatively low average values of projects in Sweden (40%), the Netherlands (43%) and Finland (48%), for example, are connected to the announcements of smaller companies with a lack of experience in battery production or companies already struggling with financial problems. The likelihood of implementation for projects in Germany is in the lower middle category and on average at 60%.

According to our model calculations, the countries with the highest theoretical cell production capacity in Europe will be Poland and Hungary over the next few years, before Germany may emerge as the largest cell producer at the end of the decade (approx. 350 GWh in 2030). This value has declined since last year by almost 100 GWh. Next to Germany, Europe's second largest producer could be Hungary (230 GWh), followed by countries such as Spain, France, Poland and the UK with 100 GWh to 150 GWh of theoretical production capacity. In Sweden, a large number of announcements were cancelled, so that the expected production capacities in 2030 are only around 40 GWh. Next to those countries, relevant cell production will be established in countries such as Norway, Portugal and Serbia towards the end of the decade. The production capacities for individual European countries in 2030 are shown in Figure 5.

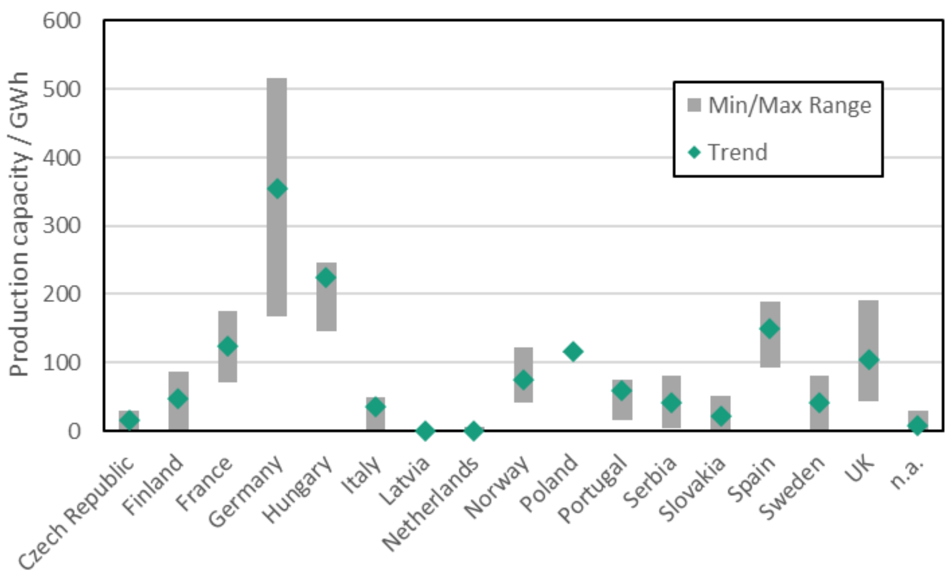

Figure 5. Country-specific range of theoretic production capacities in 2030.

It should be noted that our results are purely related to individual projects. We make no statement about the general suitability of individual European countries as production locations for battery cells.

3.5. Production Capacities and Real Production Output

The capacities mentioned in the announcements and taken into account in our model can be described as theoretical and correspond, for example, to a machine capacity at 100% utilisation and up-time. Literature values for the delay, capacity utilisation and scrap were assumed for the calculation of a more realistic "real" production output (more details in Supplementary Materials).

A scrap rate of 7.5% was assumed. The utilisation rate for the gigafactories, which was assumed to be 80%, makes an even larger difference. In addition, we assumed a delay for the start of production of one year on average.

Taking into account these factors, compared to the theoretical production capacity in our trend scenario, there may be a further reduction of the actual production output in 2030 by around 35% due to scrap, capacity utilisation and the delay in construction projects. The production capacity output, shown in Figure 3b, is thus expected to be approx. 210 GWh in 2025 (min 190 GWh, max 220 GWh) and to grow strongly to up to 1 TWh per year in 2030 (min 0.8 TWh, max 1.1 TWh).

3.6. Production Output of Different Battery Cell Chemistries

As shown in Figure 6, the majority of the cells produced will be based on NMC chemistry (ca. 510 GWh). This is significantly more than the projected production output for LFP, which amounts to around 170 GWh in 2030. We could not allocate 260 GWh of production output (27%) to any particular cell chemistry, as the information was not publicly available.

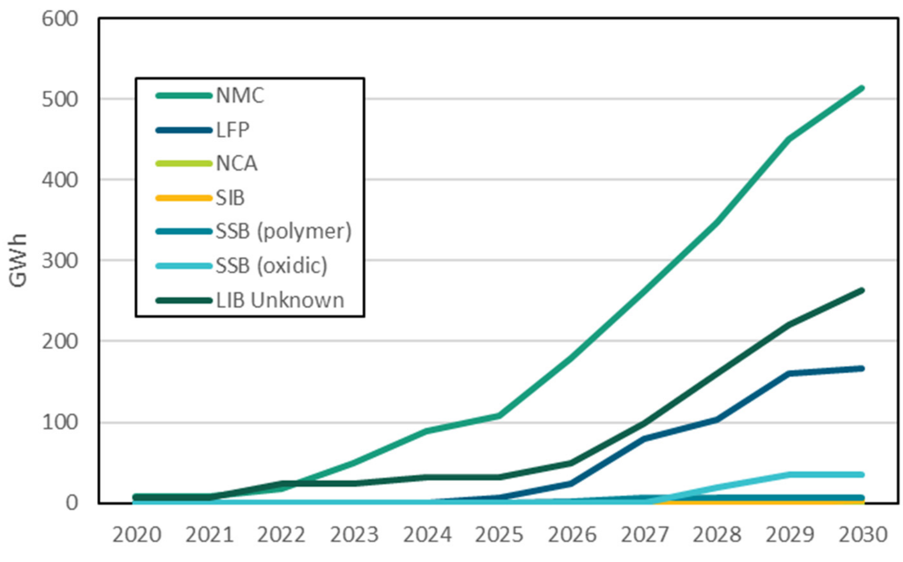

Figure 6. Production output of different cell chemistries in Europe in the trend scenario.

To date, more than 99% of production capacity in Europe is for LIBs. While the production of SIBs is currently being ramped up in Asia in particular [37], very little production capacity has been announced here for both SIB and solid-state batteries (SSB) (<10 GWh by 2030).

4. Discussion

4.1. Validation and Limits of Modelling

The theoretical production capacity resulting from the model is very well within the range of the forecasts of, e.g., VDI/VDE (920–1600 GWh) [23] or Roland Berger (1435 GWh) [12]. Individual studies by, e.g., Avicenne (700 GWh) [21] or IEA (770 GWh) [22] are somewhat more conservative, others like T&E (1725 GWh) [2] are more more optimistic. The predicted output of cells is also in line with literature values. VDI/VDE estimate this at 850–1300 GWh, Avicenne is more pessimistic with 550 GWh production output [21] and T&E calculates 1170 GWh [2]. The comparison to other studies listed in Table 6 shows that our results are in line with the expectations of various analysts.

Table 6. Literature overview of production capacity forecasts for Europe in 2030.

Study	Type	Year	Theoretical Capacity	Production Output	Reference
FhG ISI	Study	2024	1.2–1.7 TWh	0.8–1.1 TWh	
Avicenne	Market Study	2022	700 GWh	550 GWh	[21]
BMWK	Report	2023		713–1197 GWh	[61]
IEA	Report	2023	770 GWh		[22]
McKinsey	Report	2023	1235 GWh		[9]
Roland Berger/PEM	Report	2023	1435 GWh		[12]
T&E	Report	2023	1765 GWh	1374 GWh	[29]
VDI/VDE	Report	2023	920–1600 GWh	850–1300 GWh	[23]
EIT	Report	2024	1144–1800 GWh		[24]
PEM	Report	2024	2000 GWh		[25]
PwC Strategy&	Report	2024	1600 GWh	1100 GWh	[26]
T&E	Report	2024	1725 GWh	1170 GWh	[2]
VDI/VDE	Report	2024	1500 GWh	530–900 GWh	[27]

We used some simplifications and assumptions for the forecast model in order to have a procedure that is as generally valid as possible and that can also be transferred to regions outside Europe. One point of discussion certainly is the values for the likelihood of implementation of different evaluation categories on the basis of expert opinions. Even when working with a PERT distribution and a variation of different factors, systematic errors cannot be ruled out. For example, collective misjudgements regarding the importance of the 11 topics are possible. Like all players in the battery field, experts can also be subject to a bias resulting from the current state of the industry and tone of voice in media coverage. A sensitivity analysis (Supplementary Materials) shows that the implications of an over- or underestimation of a single risk factor is rather low. Incorrect categorisation of individual projects and the resulting incorrect calculation of the likelihood of implementation of individual construction projects (exemplified by a calculation with a modified *Construction Status* and a different *Offtake* evaluation category) exists in the range of scenarios shown.

Of course, the list of 11 topics can also not be considered complete and does not reflect all factors influencing implementation. One aspect repeatedly subject of debate, is the skilled workers required for the gigafactories [62]. The availability of sufficient personnel could potentially also be a deciding factor for a location, but it is extremely difficult to find a quantitative database for this evaluation (especially internationally).

Other factors such as bureaucratic hurdles could also influence a decision. Cell manufacturers have criticised complex approval and permitting procedures for new production sites [18], which will cause additional costs and, in particular, longer construction times. However, this location factor is also difficult to map across different countries. The analysis of the individual cell and production technologies was also deliberately omitted, since it was assumed that all manufacturers produce LIB without large technological differences (apart from the cell chemistry). However, if more and more production capacities for next-generation battery technologies (e.g., solid state) are announced, a technology factor should certainly be included in the model to take into account maturity.

Still, even this structured analysis of the announcements cannot take every possible criterion into account and may therefore overlook individual risks. Therefore, the model cannot provide absolute certainty regarding the likelihood of implementation of the individual production projects. It happens that announcements that experts believe to be certain (e.g., from an established manufacturer such as SVOLT in Germany [18]) are not realised as announced. Our primary goal was however to determine the overall production volume based on a large number of announcements and not to make a good forecast for individual plants. It is therefore suitable for a forecast of the expansion of production capacities on a larger scale from 2026 onwards, rather than for the early construction projects, which are often dependent more on strategic decisions of the individual companies.

Furthermore, it is likely that additional announcements will be made in the next few years, thus increasing the cumulative number of production announcements towards the end of the decade. The long-term explanatory power is limited because announcements are only made to a certain extent in the future.

4.2. Comparison of Production Output and Market Demand

The modelled production output of around 1 TWh is in the range of the expected demand for cells in Europe, which could amount to around 800 to 1300 GWh in 2030 [20]. This is also more than the aspirations of the Net-Zero Industry Act (NZIA) [4], which defines a minimum capacity of 550 GWh by 2030 as a political goal for European battery production. The German Ministry of Economic Affairs, for example, has set a target of supplying around 30% of the national demand for battery cells from German and European production by 2030 [63]. The battery market especially at regional level remains very dynamic in the short term. Deviations upwards or downwards between demand and production capacities are nevertheless conceivable, as the example of China (overcapacity) or Europe (import) shows. It is quite possible that there could also be overcapacity in Europe (then characterised by low-capacity utilisation at production facilities, for example).

We hence do not use the forecast battery demand as a measure for the likelihood of implementation of production capacities. It can be assumed that the export (Asian countries) and import (e.g., Europe or the US) will continue to play a substantial role. Especially, a regional production volume linked directly to demand is therefore only of limited significance for regional production capacities. Our model calculations hence result in total production capacities fitting the demand, without directly overinterpreting the quality of the result.

4.3. Delay and Cancellation of Construction Projects

Notably in 2024, there were a large number of cancellations and construction delays for gigafactories in Europe. In total, around 350 GWh of once planned capacities have already been cancelled, and a roughly equal number of production capacities are currently on hold (see Supplementary Materials).

In addition to the challenges for cell production in Europe, such as high energy costs or competing funding programs in the USA, the reasons are found in particular in the weak market demand [18,58]. Even if further announced production projects are not built, the market can still be adequately served. Thus, there is currently a consolidation of the market and the suppliers.

In addition, there are delays in construction projects due to strategic considerations about which cell chemistry should be produced in the plants. Some producers seem to follow a wait-and-see strategy of choosing the right cell chemistry and to correctly interpret market trends like the current shift from NMC chemistry to LFP [64]. During the first ramp-up of European producers, major quality challenges also arise in production, resulting in a great deal of scrap, which causes high costs [65].

5. Conclusions

We have presented a model that allows the development of scenarios for future European cell production capacities by considering 11 relevant topics for build-up and scale-up. For the first time, all announcements for the build-up of cell production capacities in a defined area (Europe) were systematically analysed and translated into scenarios for the production ramp-up in a scientific and comprehensible manner.Using the expert-based implementation probabilities compiled in this study, the model suggests that 54 to 75% of the announced capacities in Europe will be realised (1.2 GWh–1.7 GWh in 2030). This could result in a cell output of approximately 0.8 to 1.1 TWh in 2030. Although there are also some announcements that extend beyond 2030, this is not the rule. Due to the limited lead time between announcement of a project and start of production, we must assume that a list of projects for the years beyond 2030 would be highly incomplete. An extension of our model beyond 2030 is therefore not meaningful and other approaches need to be found for that.

As we have shown, there are many factors influencing the scale-up of battery production in Europe. Our model cannot reflect all influencing factors. However, limited to the supply side, we have developed a holistic picture of the industry with 11 different topics and risk factors. Economic policy measures will play a decisive role in strengthening future European battery production, possibly following the recent delays and failure of projects to set up new production facilities. These measures are difficult to predict and can be considered, for example, when comparing several regions by adjusting the likelihood of implementation of the *Subsidies and Policies* topic and the *Construction Status*.

To optimise the methodological approach, it makes sense to benchmark and identify the production capacities that have been developed up to that point and, in particular, the failed projects in a few years' time. A comparison of the delayed or cancelled projects with the risk topics may allow a refinement of the weighting factors of the 11 topics and could reduce possible sources of error in the expert-based approach used in this work.

Another research opportunity is to conduct secondary analyses based on the model results. On country level, for example, valuable data about investments in the battery industry of respective countries, the demand for skilled workers or the energy consumption of the gigafactories can be calculated.

One advantage of our method is that it can, in principle, be applied to other industries. This includes identifying key risk topics, weighting them (through expert interviews or, if available, historical data) and creating overall scenarios based on individual announcements. Many industries have similar dependencies on energy and labour costs, for example, so that parts of our model can even be adopted if necessary. Since the methodology can be extended to include any number of topics, other factors, e.g., technological competitiveness, can also be added.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/batteries11020076/s1, Table S1: Likelihood of implementation of the individual evaluation categories in the various Construction Statuses. Table S2: Assigned evaluation categories of the production projects, analysed in the benchmark with the resulting likelihood of implementation. Table S3: Outcome of new simulations (trend result for the theoretical production capacity) when the likelihoods of implementation for different topics is changed by 20 percent. Table S4: Outcome of new simulations (trend result for the theoretical production capacity) when lowering or raising every possible evaluation category of the Construction Status or the Offtake risk factor [66–87].

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Conflicts of Interest: The authors declare no conflicts of interest.

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