



## Research article

# Bridging the global cost gap in battery cell manufacturing – From locational factors to factory planning, and policy design



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## ABSTRACT

The accelerating demand for lithium-ion battery (LIB) cells necessitates a strategic, cost-competitive, and resilient battery production landscape. This study combines a battery market structure analysis with an extension of a techno-economic cost model to assess the impact of factory planning, location-specific factors, and policy instruments on LIB production economics. While the political stability, the energy mix, and the financial incentives shape site attractiveness, a scenario analysis demonstrates that China's cost advantage stems less from geographic location and more from lower material and equipment costs and superior production efficiency. Ramp-up delays are identified as a major cost risk, particularly in later stages, where weekly delays can add costs of \$1 M per GWh of annual output. Furthermore, different policy tools are compared, including direct per-kWh subsidies, investment-based payments, and import tariffs. Only sustained operating subsidies substantially reduce production cost gaps compared to China, while one-time incentives show limited impact. To balance cost-effectiveness and fiscal feasibility, a combined approach of different measures may be beneficial. The findings of this work underscore the importance of aligning industrial policy, factory planning, and research investment to secure sustainable competitive advantages in the evolving global battery market.

## 1. Introduction

The transition to climate-neutral energy technologies has positioned lithium-ion batteries (LIBs) as a key element of the global energy and mobility revolution. As electrification and renewable energy adoption accelerate, the demand for LIBs is substantially increasing, and the ability to produce these cells at scale has become a key economic and geopolitical factor [1]. However, the current battery market is heavily dominated by Asian manufacturers, controlling more than 80% of the global LIB production capacity [2]. This power concentration has created strong dependencies on a few key players, leading to supply chain risks, price volatility, and strategic vulnerabilities for regions without domestic production capabilities [3]. In response, the European Union has set ambitious goals to become a leader in sustainable battery technologies and establish a competitive battery industry, recognizing that a resilient and sustainable supply chain is essential for industrial sovereignty and long-term economic stability [4].

Despite substantial efforts, building a GWh-scale battery production in Europe remains challenging. Initiatives such as those from the company Northvolt illustrate the complexity of scaling up manufacturing, from

securing raw materials and establishing supply networks to overcoming high expenditures and regulatory hurdles [5,6]. Given these challenges, understanding the factors that influence the competitiveness of large-scale battery production is crucial for effective industrial policy and strategic investment [1].

This article analyzes the current battery production market, focusing on location-based factors and the underlying market structure. To support this analysis, an extension of an existing battery production cost model was introduced, enabling a detailed assessment of how the factory planning phase impacts production economics. Using this model, a scenario analysis was conducted to evaluate how the production location, the ramp-up phase, and political support measures from the government influence the competitiveness of LIB manufacturers. By quantifying these effects, insights into the key levers that can drive the success of a sustainable and competitive battery industry in Europe were provided.

## 2. The market for battery cell production

To account for external factors influencing LIB production that are not directly captured by process-level cost modeling, established

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strategic analysis frameworks were employed. The Political, Economic, Social, Technological, Ecological, Legal (*PESTEL*) framework structures location-specific boundary conditions, while Porter's 5 forces characterizes the market structure and dynamics. These frameworks serve as a structured link between qualitative industry characteristics and the parameterization of the techno-economic scenario analysis.

### 2.1. Geographical analysis

To analyze the global market for LIB production, location-related factors for a LIB Gigafactory were compared for a representative selection of global locations [3,7]. These locations comprise Germany (GER), Hungary (HUN), Sweden (SWE), the United States of America (USA), Canada (CAN), and China (CN). To assess these locations, the so-called *PESTEL* analysis was conducted, considering political, economic, social, technological, ecological, and legal factors [8]. Its purpose is not to derive direct model inputs but to systematically contextualize the external conditions under which the techno-economic scenarios are defined and interpreted. Due to the large number of country-specific indicators required for this comparison, the detailed analysis is presented in [Supplementary Note S1](#), which offers an extensive collection of data and figures.

### 2.2. Market structure analysis

The market structure of the LIB industry and its current situation were analyzed by applying Porter's 5 forces framework, which is usually used to analyze an industry's competitiveness, attractiveness, and profit potential [9]. This analysis tool serves a complementary role by characterizing the competitive landscape and value-chain structure of the LIB industry. Together, *PESTEL* and Porter's 5 forces analyses provide a structured qualitative foundation for interpreting the cost and policy scenarios examined in this work. The Porter's 5 forces framework suggests that the structure of a market is determined by the following 5 factors: The rivalry among existing competitors, the power of buyers, the threat of substitute products or services, the threat of new market entrants, and the power of suppliers. In the following, these factors are discussed for the current LIB industry.

#### 2.2.1. Rivalry among existing competitors

The competitive rivalry among LIB manufacturers is primarily driven by market share and costs. Currently, Chinese LIB manufacturers dominate the global production. Despite new market entrants, Bhandari et al. [2] predict that Chinese producers will maintain their leading position. While their global market share is expected to decline due to increased production capacity in Europe and North America, overall demand for LIBs continues to grow, temporarily reducing competitive pressure [10]. However, surplus production capacity is emerging, which counteracts this effect and intensifies competition. Chinese LIB manufacturers benefit from extensive production experience, giving them an advantage over newer European and North American producers. This expertise results in shorter cycle times and higher overall equipment effectiveness, leading to lower production costs [11–13]. Additionally, their scrap rates are lower, as many Western producers are still in the ramp-up phase and face higher defect rates [12].

Beyond cost advantages, product differentiation through unique selling propositions influences the market position. Asian manufacturers compete primarily on price [13], while European companies focus on sustainability [14]. Government regulations further shape the market. The Inflation Reduction Act (IRA) has made the USA an unattractive production site for Chinese companies, as they are excluded from receiving IRA incentives, exacerbating the ongoing trade tensions amidst the import tariff conflict. Consequently, the European market has become increasingly attractive for Chinese producers, intensifying price competition. At the same time, European manufacturers were prone to shift investments in new production capacities to the USA to

profit from the IRA incentives [3,14]. However, the One Big Beautiful Bill Act (OBBBA) that recently became effective is eliminating the IRA electric vehicles (EV) and battery production tax credits, which is expected to lead to a considerable decline in battery investments in the USA [15,16].

#### 2.2.2. Power of buyers

The bargaining power of customers in the LIB market depends on factors such as switching costs and supply-demand dynamics. Switching suppliers requires a product audit to ensure quality standards, incurring both financial and time efforts [17]. The current market situation favors customers due to oversupply. Chinese LIB manufacturers face overcapacity and are forced to lower prices to maintain sales, increasing customer leverage [18]. Even producers without excess capacity experience price pressure due to low-cost competition from China [3]. This price competition is expected to persist, further shifting bargaining power to the customers. However, established manufacturers mitigate this by serving multiple customers, reducing dependence on single buyers. For example, LG Energy Solution supplies Tesla, General Motors, and Volkswagen, while CATL serves Chinese EV makers and global players like Tesla and BMW [19,20]. Product quality also influences bargaining power, as LIBs determine key EV performance metrics such as range and charging time. Manufacturers offering higher-quality cells, such as cells with superior energy densities, can strengthen their negotiating position [21]. Nevertheless, since EV makers source LIBs from multiple suppliers, currently, no single manufacturer holds a dominant bargaining advantage [22].

#### 2.2.3. Threat of substitution

To assess the substitution risk for LIBs, a distinction is made between applications in the EV and stationary energy storage (SES) sectors, both of which exhibit significant demand and projected growth [10]. The evaluation considered mass production readiness, cost, material availability, energy density, and safety. Each category was rated on a scale from 1 to 5, with 3 being comparable to LIBs, 5 being superior, and 1 being inferior. A weighted sum of these ratings determined the substitution risk, with weighting factors derived from a pairwise comparison (cf. [Supplementary Table S2](#)). Both the weighting factors and the evaluation criteria are rated based on the authors' assumptions. Technology transfer effects were not considered [23]. The overall risk was then assessed and calculated by dividing each technology's score by the LIB score. Values below 1 indicate low risk, a value of 1 indicates full substitution potential, and values above 1 signal a high substitution threat. For EVs, sodium-ion batteries (SIBs), all-solid-state batteries (ASSBs), and fuel cells were analyzed, as these are the dominant options for electric propulsion systems [23–25]. E-fuels were excluded because of their limited technological maturity, and to keep the analysis focused on emission-free energy storage systems, thereby ensuring the comparability of the technologies [26]. The results are listed in [Supplementary Table S3](#) and indicate that SIBs pose the strongest competition to LIBs, while ASSBs and fuel cells require further technological advancements before posing viable substitutes.

For SESs, SIBs, ASSBs, vanadium redox flow batteries (VRFBs), and sodium-sulfur high-temperature batteries (SSHTBs) were analyzed, as they are already in use [23,25]. The results (cf. [Supplementary Table S3](#)) show that SIBs pose a greater risk of substitution for LIBs in this sector than in EVs, as energy density is less critical [23]. VRFBs and SSHTBs present a lower substitution risk, offering niche advantages without entirely replacing LIBs. The evaluation details are provided in [Supplementary Note S2](#).

#### 2.2.4. Threat of new entrants

Entering the LIB production market requires significant investment, as establishing a GWh-scale production demands billions in capital [27]. Raising funds is particularly challenging, with Chinese producers already facing difficulties securing new capital for expansion. For new

entrants, the financial risk is even higher [3]. Additional risks include construction delays, production ramp-up issues, and high scrap rates. A 6-month delay of a factory with an annual capacity of 30–40 GWh can result in €1–2B in lost revenue, while each additional percentage point of scrap in a 10 GWh factory adds approximately €5 M in annual costs [3,14]. New competitors, especially in Europe and North America, lack the experience of established producers [3,12]. They also do not benefit from economies of scale, leading to higher production costs [2]. Moreover, patent protections by existing manufacturers, which are particularly dominated by China (cf. Supplementary Fig. S4a), serve as an additional market entry barrier [28]. While high market demand typically lowers entry barriers, the LIB industry faces overcapacity, increasing the financial risks for new entrants [10]. Regulatory challenges further complicate market entry, particularly in Europe, where bureaucratic hurdles such as environmental regulations slow the approval process [3,14,29]. Finally, securing supply chains is critical. Established Asian manufacturers have already integrated vertically to ensure raw material availability and access to high-quality production equipment. New entrants that lack these established supply chains face further disadvantages [2,3,5].

### 2.2.5. Power of suppliers

Larger companies generally possess greater bargaining power due to economies of scale [2]. This dynamic is also evident in the battery production equipment market, where suppliers can strengthen their position by demonstrating proven machine functionality, which is a key selection criterion of LIB manufacturers. Additionally, rapid delivery and scalability are critical requirements for suppliers to meet customers' needs [3,30]. Competitive pricing significantly increases supplier power, particularly in equipment procurement. In this regard, Asian suppliers hold an advantage, offering production equipment at roughly 50% lower costs than their American or European counterparts [13,14]. However, due to the high demand for production equipment driven by numerous planned gigafactories, the bargaining position of all non-Asian suppliers is strengthening [31]. Beyond equipment, raw material suppliers, particularly for lithium and nickel, hold considerable power due to limited resource availability [2]. In response, recycling is becoming increasingly important for securing raw materials and reducing dependence on primary raw material suppliers, thereby weakening their bargaining power [2,14,32]. However, regardless of the raw material supply, component suppliers play a central role in closing the value chain, strengthening their position [33].

### 2.3. Summary

The *PESTEL* analysis demonstrated geographical differences when considering LIB production sites. The most attractive locations for gigafactories depend on a combination of incentives, labor costs, political stability, and energy availability. Among the investigated locations, Canada, Sweden, and Germany offer the most stable political

environments and the strongest renewable energy integration in production, making them attractive for sustainable production. China remains dominant in raw materials and cost efficiency but faces geopolitical challenges and trade restrictions. The USA and Canada provide financial incentives to reshape investment decisions. However, the impact of the OBBBA, which stopped the IRA incentives, remains uncertain.

The LIB market is currently marked by oversupply, driving down prices and shifting power to customers. While the demand continues to grow, the surplus production capacity intensifies competition, especially between Chinese and European manufacturers. Asian companies benefit from established supply chains and lower costs, while Western players differentiate through sustainability and regulatory compliance.

Strategic decisions by both LIB manufacturers and policymakers are essential to address the current challenges in the European market and build a competitive, resilient LIB production industry. To support this, it is crucial to evaluate the economic impact of scaling up a gigafactory and assess the effectiveness of various political support measures. This analysis helps identify key levers for ensuring cost-competitive LIB production. The scenario analysis in the following section points out these effects using a LIB cost model, which is based on Lechner et al. [34] and extended by a more detailed cost analysis.

## 3. Scenario analysis – results and discussion

The production scenario considered for the following scenario analyses is provided in Section 5.1 of the Methods and includes an explanation of the process chain, as well as production-based and cell-based parameters.

### 3.1. Impact of production location

To assess the impact of the production location on the production costs, the selected countries from the *PESTEL* analysis were considered. Due to uncertainties in the material prices and production efficiencies, only the location-specific parameters, such as energy, personnel, and building costs, were varied. The planning and ramp-up schedule for the factory is assumed to be equal for all locations and is shown in Supplementary Fig. S6. While uncertainties in input parameters such as material prices or ramp-up performance exist, the objective of this study is to identify structural cost differences rather than to quantify probabilistic outcome ranges. By holding constant experience-based factors such as production knowledge, ramp-up maturity, and firm-specific vertical integration, a controlled comparison of location-specific cost drivers is enabled. This also allows assessing how industrial know-how can affect production costs, which is subsequently examined using China as an example. An overview of the considered parameters for each location is provided in Table 1, as well as Supplementary Table S7.

**Table 1**

Overview of the location-specific parameters considered in the scenario analysis. Data derived from [34–52], see Supplementary Table S7 for direct assignment.

Parameter	Unit	Germany	Sweden	Hungary	USA	Canada	China
Supporting staff wage	\$ h <sup>-1</sup>	40.72	40.42	12.13	33.27	26.22	6.95
Specialist wage	\$ h <sup>-1</sup>	51.29	50.91	15.71	41.91	33.03	8.75
Indirect staff wage	\$ h <sup>-1</sup>	66.42	65.94	7.04	54.27	42.77	11.35
Cleaning staff wage	\$ h <sup>-1</sup>	28.51	28.31	10.80	23.30	18.36	4.87
Building cost factor	\$ m <sup>-2</sup>	3536	3571	3182	3501	3501	2652
Property cost	\$ m <sup>-2</sup>	80.74	81.55	72.67	79.93	79.93	60.56
Office rent	\$ m <sup>-2</sup>	25.50	34.83	14.14	24.69	13.96	41.34
Electricity price	\$ kWh <sup>-1</sup>	0.207	0.098	0.216	0.089	0.088	0.084
Gas price	\$ kWh <sup>-1</sup>	0.058	0.072	0.063	0.011	0.017	0.047
Corporate tax	%	29.9	20.6	10.8	26.6	26.5	25.0

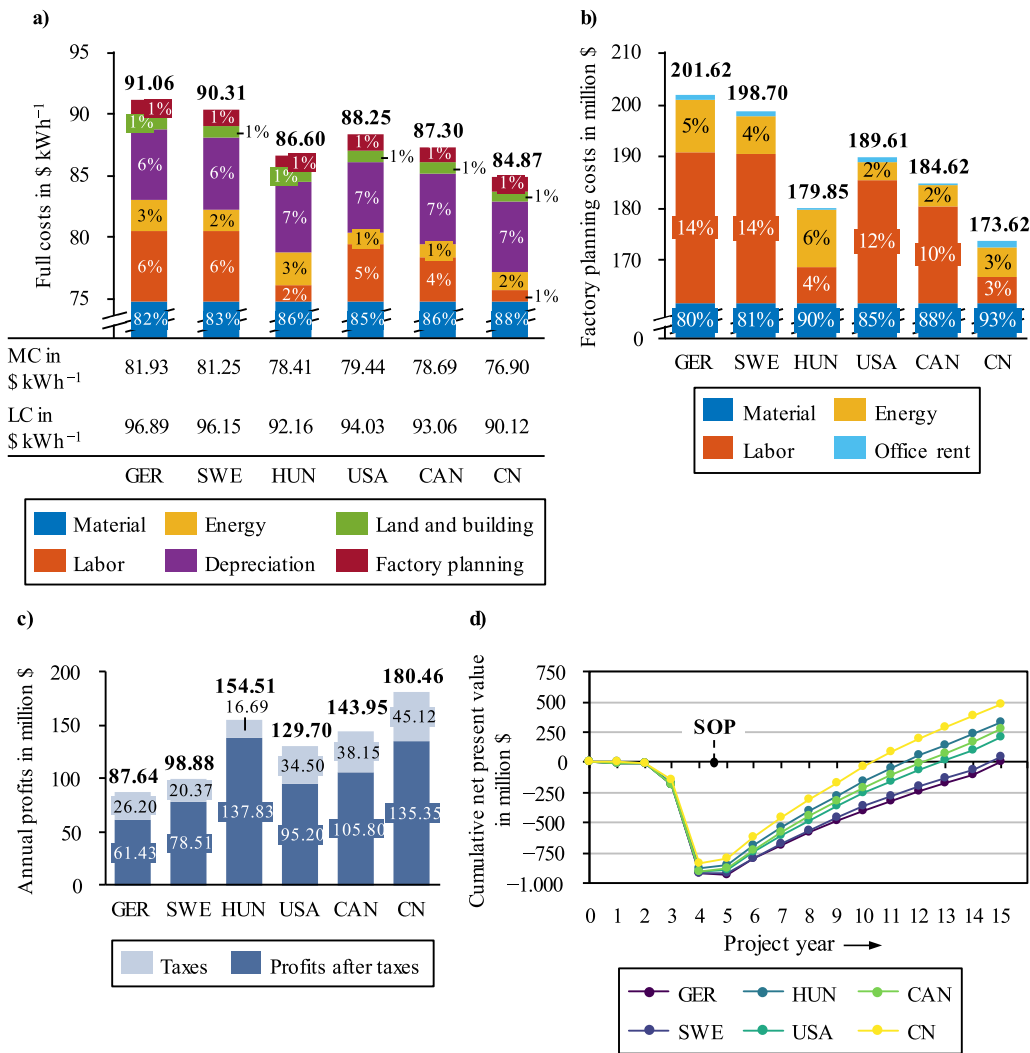


Fig. 1. a) The full, marginal, and levelized costs, b) the factory planning costs, c) the annual profits before and after taxes, and d) the cumulative net present value flow over the project duration for the investigated production locations. The annual profits and the net present value flow are calculated based on the German levelized costs of 96.90 \$ kWh<sup>-1</sup> (Figure may not sum up to 100% because of rounding). MC = marginal costs; LC = levelized costs; SOP = start of production.

### 3.1.1. Location-based comparison

Fig. 1a presents the full, marginal, and levelized costs of the 6 global production locations. The full costs comprise expenses for materials, labor, energy, depreciation, land and buildings, maintenance, and factory planning. They vary across the locations, ranging from 91.06 \$ kWh<sup>-1</sup> in Germany to 84.87 \$ kWh<sup>-1</sup> in China. Hungary ranks second-lowest at 86.60 \$ kWh<sup>-1</sup>, primarily due to low labor costs, which account for less than 2% of the full costs in both Hungary and China. The USA and Canada exhibit relatively low energy cost shares, reflecting their favorable electricity prices. The material costs represent the largest share of the full costs, amounting to a minimum of 82% in Germany and increasing to a maximum of 88% in China. This increase is due to lower contributions from other cost components, such as labor and energy, in countries with overall lower costs. The marginal costs range from 81.93 \$ kWh<sup>-1</sup> in Germany to 76.90 \$ kWh<sup>-1</sup> in China. While the location ranking remains consistent with the full costs, the difference in marginal costs between the locations is smaller because they exclude location-specific fixed costs such as land and building expenses. Driven by the full costs, the levelized costs are highest in Germany (96.89 \$ kWh<sup>-1</sup>) and lowest in China (90.12 \$ kWh<sup>-1</sup>).

The factory planning costs are shown in Fig. 1b and include material, labor, energy, and office rental expenses. The total planning costs range from \$201.62 M in Germany to \$173.62 M in China. The ranking of locations in terms of planning costs corresponds to the full costs

ranking, which is plausible since most cost categories, except for land and construction, affect both planning costs and full costs. In contrast to the full cost structure, the share of labor costs in factory planning is significantly higher at all sites. This is because material costs are mainly incurred just in the ramp-up phase, and material costs are the primary cost driver during full-scale LIB production [34].

As shown in Supplementary Fig. S1b, nominal corporate tax rates vary across the 6 analyzed production locations. To determine the annual profit for the production at each site, the levelized costs from the German site were used as a reference, as it is the highest among all locations. This approach ensures that production remains economically viable at all sites. Since the levelized cost values were rounded up, a profit is also generated in Germany under this assumption. Fig. 1c presents the pre-tax and post-tax annual profits. While the pre-tax profit in Hungary is \$25.95 M lower than in China, the post-tax profit in Hungary is \$2.48 M higher than in China. This is due to Hungary's comparatively low nominal corporate tax rate of 10.8% [52].

Fig. 1d illustrates the cumulative net present value over the full project duration, which spans 14.5 years. This includes 4.5 years of factory planning and 10 years of production, assuming that no product change will take place. The payments are accounted for at the end of each year. To ensure comparability across locations, a uniform reference price based on the levelized production cost of the German base scenario is applied when calculating net present values. This assumption reflects a hypothetical common

market environment, allowing comparison of payback periods and relative cost competitiveness without implying location-specific profitability. In the first 2 project years, the net present value remains close to zero because only factory planning costs are incurred, and no major investments are made. In the third year, the first payment for buildings and infrastructure leads to a notable drop in the net present value. This decline continues in the fourth year, which includes a second infrastructure payment and 2 payments for production equipment. A positive change in the net present value slope between years 4 and 5 marks the end of the factory planning phase. With the start of production in year 5, cost differences between the locations become apparent. The net present value at the Chinese site increases most rapidly, driven by its lower production costs. In China, the payback period is 10 years, including 4.5 years of planning and 5.5 years of production. Hungary follows with a payback period of roughly 11.5 years. Canada and the USA reach payback after 12 and 12.75 years, respectively, while in Sweden, the project reaches the break-even point approximately after 14.5 years, so 6 months before the end of the production period. Since the German leveled costs served as a baseline, the payback period equals the overall production period. In the final project year, a slight uptick in net present value is observed across all locations. This is attributed to the sale of buildings and infrastructure, which are not fully depreciated by the end of the production phase.

### 3.1.2. Cell cost derivation – China

To enable a controlled comparison between production locations, experience-driven cost reductions and location-specific material price differences are not parameterized individually. Because quantitative evidence for very low realized costs is mainly available for the Chinese market, the following analysis adopts a reverse approach to estimate the cost advantages required to reach reported price levels under otherwise uniform baseline assumptions.

As LIB prices from Chinese manufacturers are reported to be much lower than shown in Fig. 1a, the potential levers for the low cell prices from the Chinese market were identified. Based on reported cell prices of around 60 \$ kWh<sup>-1</sup> for high-Ni LiNi<sub>x</sub>Mn<sub>y</sub>Co<sub>z</sub>O<sub>2</sub> (NMC) chemistries from China [7], a reverse approach was applied to estimate potential material prices for Chinese manufacturers. This was done by first considering operational factors, which created a price corridor within which material costs could align with the reported cell price of 60 \$ kWh<sup>-1</sup>. Fig. 2 illustrates this step-by-step derivation of the reduced full cost values, based on Chinese LIB production data.

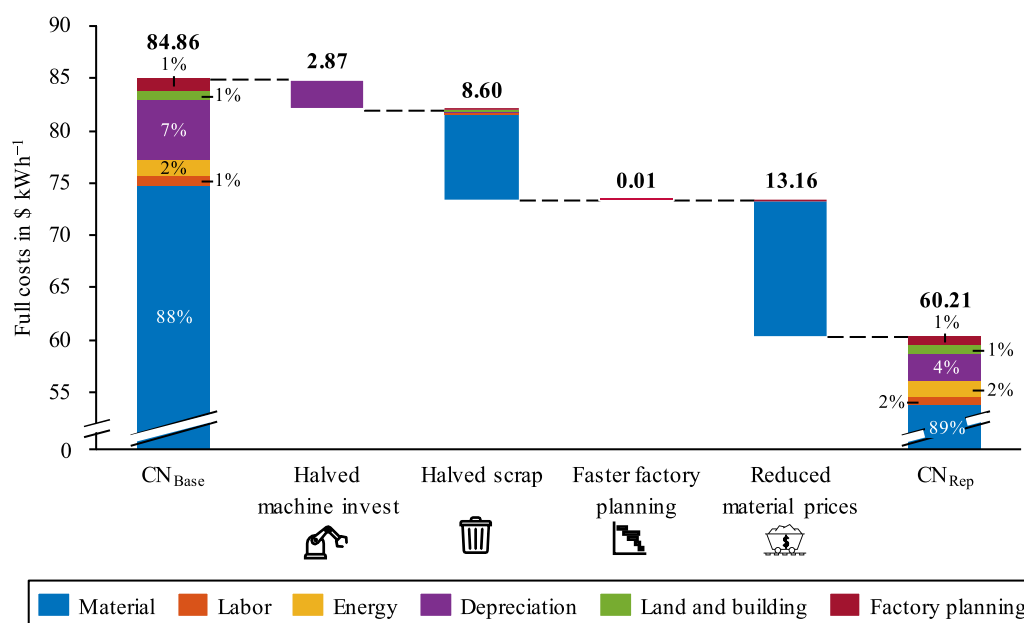
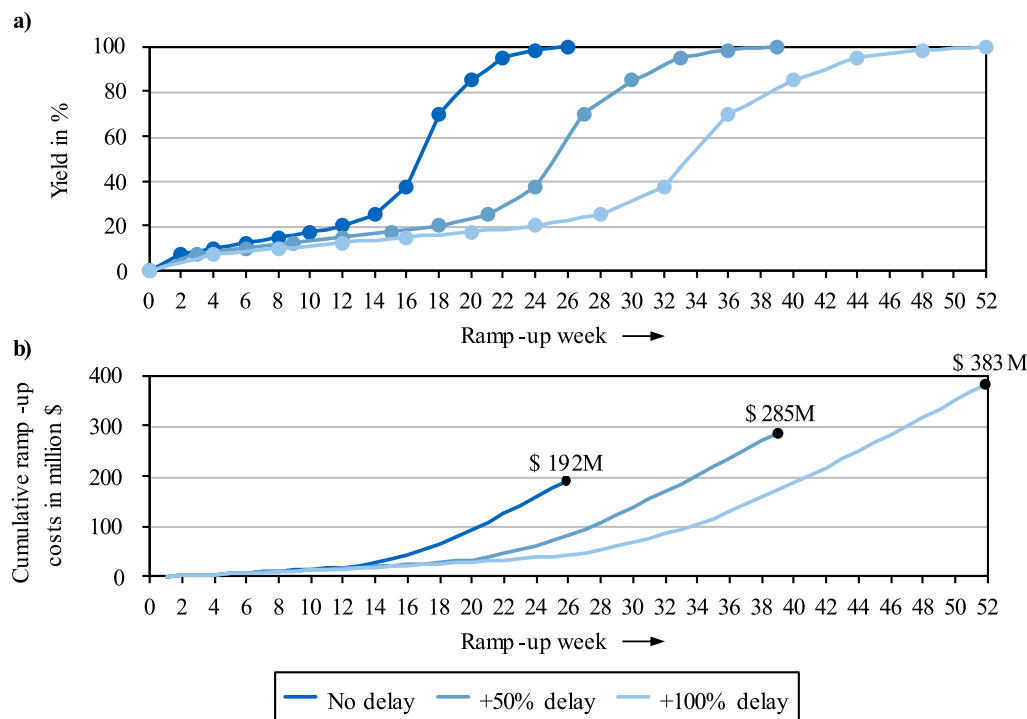


Fig. 2. Step-by-step derivation of the reported optimized Chinese full cost value CN<sub>Rep</sub> (Figure may not sum up to 100% because of rounding).

As the parameters for the production equipment used in the cost calculation are primarily sourced from European suppliers, the prices must be adjusted. Machines from Chinese manufacturers are estimated to be half as expensive as those from European suppliers [13], so the investment costs for the machines were halved in the first step. This led to a reduction of 2.87 \$ kWh<sup>-1</sup> in the resulting full costs, driven by lower depreciation and maintenance costs. Furthermore, established Chinese cell manufacturers benefit from production experience, which enables them to achieve lower scrap rates compared to newer companies [7]. To reflect this, scrap rates for each process step were halved, resulting in a cost decrease of 8.60 \$ kWh<sup>-1</sup>, mainly due to a more efficient material usage. This scrap reduction also impacts other cost categories, as fewer machines are needed to reach the required output. Leading Chinese cell manufacturers are also likely to realize the factory planning in a shorter timeframe. According to expert interviews, the start of production in China can be reached within 2.5 years due to streamlined regulatory procedures. This accelerated planning phase reduces the full costs by an additional 0.01 \$ kWh<sup>-1</sup>. The last step considered in the cost derivation process involves the material prices. Through vertical integration, Chinese cell producers often obtain significantly lower prices than their global competitors [2]. Assuming a 19.5% reduction in material prices, the total full costs decline to the estimated 60 \$ kWh<sup>-1</sup>, which corresponds to cathode active material priced at 20.12 \$ kg<sup>-1</sup> and anode active material at 4.43 \$ kg<sup>-1</sup>. Overall, the material price reduction amounts to 13.16 \$ kWh<sup>-1</sup>. This step-by-step breakdown highlights not only the specific cost advantages of global market leaders but also the significant impact of reduced scrap rates, which can result from both experience and technological innovation [53]. Furthermore, it emphasizes the strategic importance of securing access to raw materials at the lowest possible prices. It should be noted, however, that the figures presented do not account for any subsidies provided by the Chinese government, as such support measures can hardly be quantified. Nevertheless, it is likely that such measures contribute to the low cell prices reported in the media.

### 3.2. Impact of ramp-up speed

To illustrate the impact of the ramp-up duration on the factory planning costs, Fig. 3a presents the assumed production yield curve of the ramp-up, while Fig. 3b shows the cumulative ramp-up costs for a 15-GWh production in Germany under 3 ramp-up scenarios: no delay, a +50% delay, and a +100% delay in production ramp-up. The calculated ramp-up costs include material, labor, energy, and rental costs. All



**Fig. 3.** a) Depiction of the production yield curves over the ramp-up phase for different ramp-up curves, and b) the corresponding cumulative ramp-up costs for a 15-GWh production in Germany.

scenarios are based on the same S-shaped ramp-up curve depicted in [Supplementary Fig. S7](#), with the delayed scenarios reflecting a uniform stretching of this curve. As a result, the weekly ramp-up cost profiles are also stretched. In all 3 cases, a significant cost increase occurs halfway through the ramp-up phase, which is attributed to the transition from 1- to 2-shift operation in the second half of the ramp-up. This change leads to a more than 2-fold increase in weekly ramp-up costs and is reflected as a notable incline of the cumulative cost curves. Another reason for the rise in costs upon the transition to 2-shift operation is the rapid increase in target output from 40% to 60% in the production yield. At the end of the ramp-up phase, the cumulative ramp-up costs amount to around \$192 M in the no-delay scenario, approximately \$285 M in the +50% delay scenario, and roughly \$383 M in the +100% delay scenario. The visualization of the ramp-up costs in [Fig. 4b](#) highlights the financial risks associated with delays in the scale-up phase of gigafactories. Ramp-up difficulties, such as too high scrap rates resulting from uncontrolled and unstable processes, can lead to additional costs of over \$1 M per week and per GWh of planned annual production capacity. For the modeled LIB cell production with an annual output target of 15 GWh, a delay during the final third of the ramp-up phase would result in additional costs of approximately \$15 M per week. The Northvolt bankruptcy highlights that manufacturing expertise is a critical barrier to entry. Moving from laboratory prototypes to high-volume production requires the control of complex industrial processes that R&D alone cannot provide. The company's unstable ramp-up led to low yields and high scrap rates, depleting capital faster than viable products could be produced. The case demonstrates that, in the battery industry, operational excellence and reliable scale-up of precision manufacturing are the basis for long-term commercial success [\[54\]](#).

### 3.3. Impact of political support measures

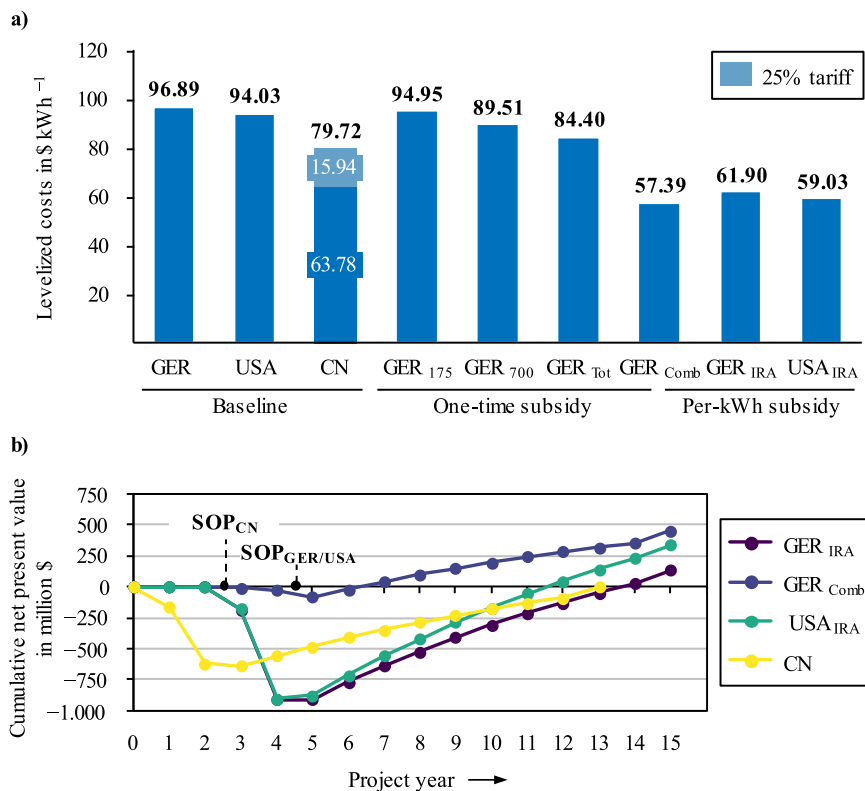
#### 3.3.1. Subsidies

As outlined in the *PESTEL* analysis, the USA and Canada primarily support the LIB production through kWh-based subsidies per cell capacity. In contrast, Europe relies on one-time subsidy payments. To assess the effect

of *per-kWh subsidies*, a tax credit of 35 \$ kWh<sup>-1</sup> is assumed, reflecting the incentive provided under the IRA. Although the IRA is no longer active in its original form, the assumed value is retained to illustrate the general impact of production-based subsidies on manufacturing economics [\[15\]](#). [Fig. 4a](#) compares the levelized costs for Germany and the USA, each without subsidy and with a 35 \$ kWh<sup>-1</sup> subsidy (GER<sub>IRA</sub> and USA<sub>IRA</sub>), to the levelized costs of a Chinese market leader. The results show that the levelized costs decrease by the subsidy amount, lowering the costs to 61.90 \$ kWh<sup>-1</sup> in Germany and 59.03 \$ kWh<sup>-1</sup> in the USA, which are below the levelized costs of Chinese producers.

To evaluate the effect of *one-time subsidy payments*, Northvolt's LIB gigafactory in Heide is used as a reference. The granted one-time payment of €700 M (converted to \$700 M at a 1-to-1 exchange rate for simplicity) corresponds to \$11.67 M per GWh of the planned annual cell output of 60 GWh. For the 15 GWh plant from the case study, this equals a \$175 M payment. [Fig. 4a](#) depicts the resulting levelized costs for Germany, considering one-time payments of \$175 M (GER<sub>175</sub>), \$700 M (GER<sub>700</sub>), and around \$1.2B to cover the total investment costs (GER<sub>Tot</sub>). The results indicate that one-time payments have a smaller impact than per-kWh subsidies. This is due to the cumulative subsidy amount, which corresponds to \$5.25B for a 35 \$ kWh<sup>-1</sup> subsidy in the case of a 15 GWh factory. In contrast, a one-time payment covering the total investment costs is 77% lower. As a result, one-time payments alone do not reduce the levelized costs to a competitive level. Moreover, this form of subsidy shifts the financial risk from the LIB producer to the government, as the payment does not guarantee the successful construction or operation of the plant. However, the LIB producer no longer faces the challenge of raising upfront capital.

Another subsidy option investigated is a combined approach of a one-time payment of \$1.2B covering all investment costs and a reduced per-kWh subsidy of 27.01 \$ kWh<sup>-1</sup> to match the cumulative funding of a credit of 35 \$ kWh<sup>-1</sup>, which is \$5.25B for a 15 GWh production. [Fig. 4a](#) compares the resulting levelized costs for this combined subsidy (GER<sub>Comb</sub>) to the levelized costs of the other subsidy formats. The combined approach yields levelized costs of 57.39 \$ kWh<sup>-1</sup>, which is lower than all other cases, including that of the Chinese producers. This



**Fig. 4.** The impact of specific subsidy forms on a) the leveled costs and b) the cumulative net present value flow compared to a Chinese price level. The net present value flow is calculated based on the Chinese leveled costs of 63.78 \$ kWh<sup>-1</sup> (without 25% tariff). GER<sub>175</sub> = one-time payment of \$175 M; GER<sub>700</sub> = one-time payment of \$700M; GER<sub>Tot</sub> = one-time payment to cover all investment costs; GER<sub>Comb</sub> = combined subsidy with one-time payment to cover all investment costs, including per-kWh payment of 27.01 \$ kWh<sup>-1</sup>; USA<sub>IRA</sub>/GER<sub>IRA</sub> = per-kWh payment of 35 \$ kWh<sup>-1</sup>; SOP<sub>CN</sub> = start of production in China; SOP<sub>GER/USA</sub> = start of production in Germany and USA.

advantage results from the time value of money, which is reflected in the net present value analysis. Subsidies granted earlier in the project have a more significant impact on the net present value than those disbursed later. In this scenario, approximately 23% of the total subsidy is paid during the planning phase, thereby increasing its effect on the net present value. Fig. 4b presents the cumulative net present value flow across the subsidy scenarios, assuming a cell price equal to the leveled costs of Chinese producers (63.78 \$ kWh<sup>-1</sup>). A gigafactory receiving the combined subsidy reaches break-even 5 to 7 years earlier than the others, and its low net present value point is several hundred million dollars higher. These differences are attributed to the upfront payment covering the investment costs, significantly reducing an early negative cash flow and shortening the payback period. The comparison of the subsidy formats demonstrates that it is beneficial for LIB producers to first receive a one-time investment subsidy, followed by ongoing per-kWh incentives. These effects arise because different subsidy formats influence cash-flow timing and risk exposure in distinct ways: one-time investment subsidies primarily reduce upfront capital risk, whereas production-based per-kWh incentives support operational cost recovery over time. Accordingly, subsidy instruments affect investment attractiveness through risk shifting and timing effects rather than by reducing system-wide production costs. The findings also indicate that substantial funding is required to match the leveled costs of Chinese producers. To achieve cost parity with Chinese competitors, Europe would need to provide cumulative subsidies of about \$23B to \$31B per year by 2030, assuming a projected annual European production output ranging from 0.8 to 1.1 TWh.

### 3.3.2. Tariffs

In addition to subsidies, import tariffs on LIB offer a way to protect a local battery ecosystem. These tariffs increase the price of imported cells and shield domestic production from cheaper foreign competitors. In the USA, a 25% import tariff was put in place for Chinese LIBs in 2024 [55]. Its effect, in combination with the IRA subsidies, is shown in Fig. 4a (cf. USA<sub>IRA</sub> vs. CN). The tariff value reflects a representative level based on available information at the time of modeling and may

not capture the most recent policy adjustments in the USA. Fig. 5a illustrates the impact of different import tariff levels on the net present value development of the LIB production, using the unsubsidized leveled costs in Germany as the sales price. A tariff as high as 51.93% was chosen, as this is the level needed to equalize the leveled costs between imported Chinese cells and those produced locally in Germany. Fig. 5a also reveals that the payback period increases disproportionately with higher tariffs, which can again be explained by the time value of money. While investment costs remain constant, higher tariffs reduce the gradient of the net present value growth, resulting in a longer break-even period. Fig. 5b summarizes potential combinations of subsidies and tariffs to reach parity with the leveled costs of Chinese producers. Assuming no subsidy is granted in Germany, a tariff of 51.93% is needed to reach price parity. If the investment costs are fully covered with a one-time payment, a tariff of 32.34% would be sufficient for price parity. Overall, this analysis shows that import tariffs can help protect the local battery ecosystem. A combination of subsidies and tariffs may offer a balanced approach that reduces the required public funding while avoiding trade conflicts caused by excessively high tariff rates.

### 3.3.3. Research funding for innovations

In addition to subsidies and tariffs, continuous funding in research and development represents an important support, aiming for innovations in product and process technologies. The effect of innovations is demonstrated by 2 exemplary cases. Based on the case study from Duffner et al. [11], the scrap rate at the end of line testing can be reduced from 5% to 1%. The lower scrap-rate assumption is used to illustrate the potential magnitude of cost reductions from improved process quality. It does not represent a current industrial benchmark but indicates what may be achievable through future process optimization and research efforts. A promising way to achieve such improvements is the application of machine-learning approaches in electrode production [56] or cell finalization [57], along with a holistic tracking and tracing system [58]. Fig. 6a illustrates the impact of the reduced scrap rate on the full costs, which is lowered by 3.82 \$ kWh<sup>-1</sup>,

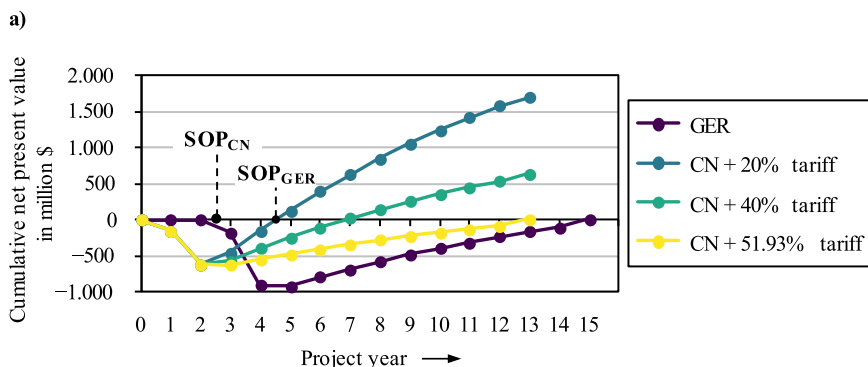


Fig. 5. a) The impact of different import tariff levels on the cumulative net present value flow and b) the required tariff rates in dependence on the subsidy form to offset the Chinese cell prices. GER<sub>175</sub> = one-time payment of \$175M; GER<sub>700</sub> = one-time payment of \$700 M; GER<sub>Tot</sub> = one-time payment to cover all investment costs; SOP<sub>CN</sub> = start of production in China; SOP<sub>GER</sub> = start of production in Germany.

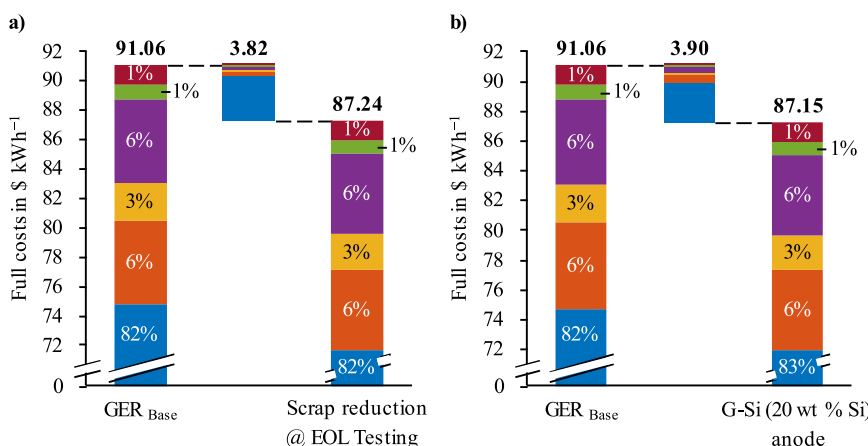
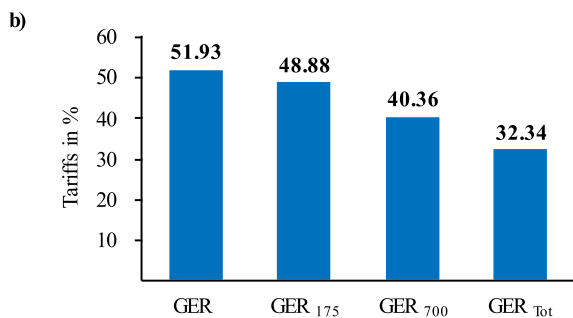
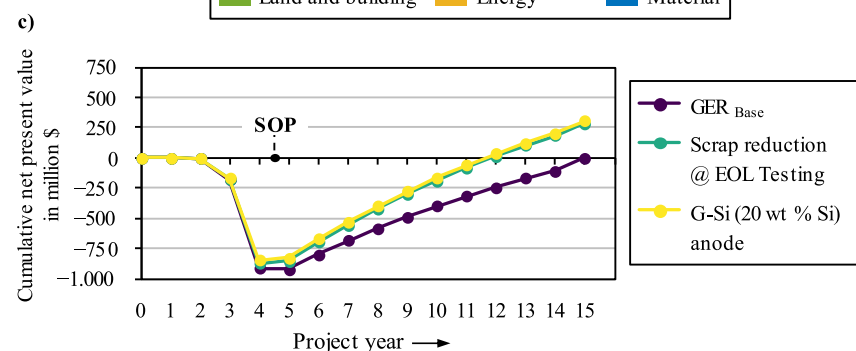


Fig. 6. Full cost reduction for a) a reduced EOL testing scrap rate from 5% to 1% due to an optimized cell finalization, and for b) qualifying a G-Si (20 wt% Si) anode. c) Net present value flow during the project time of the 2 innovations compared to the base net present value flow (Figure may not sum up to 100% because of rounding). EOL = end-of-line; G = graphite; SOP = start of production.



resulting in total full costs of 87.24 \$ kWh<sup>-1</sup>. This improvement positively affects the payback period, which is reached after twelve project years, considering levelized costs of 96.90 \$ kWh<sup>-1</sup> for the production in Germany (cf. Fig. 6b). As an example of a product innovation, the impact of qualifying silicon (Si)-containing anodes is demonstrated. Using the 4680 cell from the scenario analysis employed in this work

and incorporating a graphite anode blended with 20 wt% Si yields an energy density of 275.94 Wh kg<sup>-1</sup>, an increase of around 12% compared to the graphite-based cell. This allows for a better utilization of the passive cell components and reduces the overall number of cells that need to be produced for a specific output in GWh. Through this, the full costs can be reduced by about 4%, indicating similar cost savings to

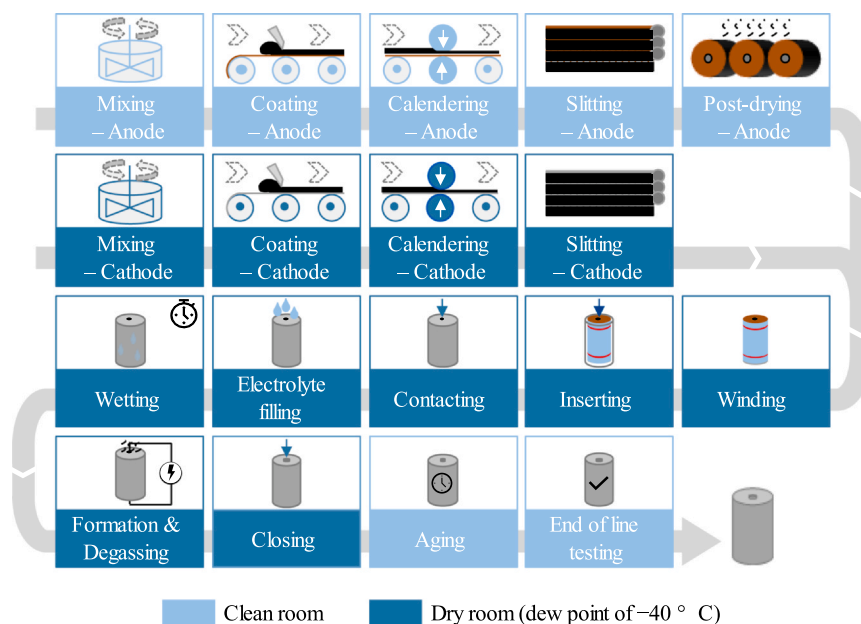


Fig. 7. Considered process chain for the scenario analysis.

those for the scrap reduction at the end-of-line testing. Accordingly, the payback period can be cut by 3 years. However, as Si-containing cells may suffer from compromised lifetimes, the effect could be weakened when considering the total cost of ownership [34]. Nevertheless, the 2 examples demonstrate the leverage of process and product innovations in reaching lower cell prices and, therefore, supporting strategic competitiveness.

#### 4. Conclusion

Within this article, the current LIB production market was analyzed, focusing on location-based factors and the underlying market structure. To support this, we introduced an extension of an existing LIB production cost model, enabling a detailed assessment of how the factory planning phase impacts production economics. A *PESTEL* analysis revealed that the attractiveness of gigafactory locations is influenced by political stability, access to clean energy, cost structures, and policy incentives. In an increasingly saturated market, the strategic positioning of production capacity becomes more critical than ever. To maintain Europe's competitiveness in the face of intensifying global dynamics, particularly from Asia and North America, industry stakeholders and policymakers must align their efforts. This involves not only optimizing local production ecosystems but also designing effective support mechanisms that enhance cost efficiency and market resilience.

Building on this, several scenario analyses were conducted. These demonstrated that China's locational advantage accounts for only a small portion of the overall cost advantage expected from its global market leaders in LIB production. For the 4680 cylindrical cell considered in this study, the full cost difference between manufacturing in Germany and China is approximately  $6.19\text{ \$ kWh}^{-1}$ . In contrast, current reports indicate that leading Chinese manufacturers achieve full costs of around  $60\text{ \$ kWh}^{-1}$ , implying a cost gap of more than  $30\text{ \$ kWh}^{-1}$  compared to German production. This suggests that the primary drivers of China's cost advantage lie in lower material and equipment costs, as well as superior production performance. The analyses also examined the impact of delays in factory planning. Only ramp-up delays were found to significantly affect LIB costs. Specifically, in the final third of the ramp-up phase, each week of delay incurs costs of approximately  $1\text{ M per GWh}$  of annual output, highlighting the critical importance of efficient production scaling. Further scenario studies on

subsidies and import tariffs revealed that the IRA has given the USA a significant advantage in strengthening domestic LIB production competitiveness. For Europe to match this advantage, it would need to provide subsidies amounting to roughly  $\$23\text{B}$  to  $\$31\text{B}$  annually, if aiming for the forecasted production output of  $0.8\text{--}1.1\text{ TWh}$  by 2030. One-time investment-based subsidies, by contrast, were shown to have a significantly lower effect and are insufficient to maintain price competitiveness with producers in the USA or China. To support local LIB production while managing public spending, a combined approach of targeted subsidies and import tariffs could be considered. However, policymakers must carefully balance the potential trade policy implications of such tariffs. Finally, the analyses underscore the importance of technological innovation. To strengthen the European battery ecosystem in the medium to long term, active research and development support is essential, not only to foster innovation but also to secure sustainable cost advantages.

#### 5. Methods

##### 5.1. Production scenario of case study

The scenario analyses are based on the production scenario outlined in Lechner et al. [59] with a 4680-format cylindrical cell production and an annual output of 15 GWh. The considered process chain is depicted in Fig. 7. For the cells,  $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$  (NMC811) is used as the cathode active material, considering both the cell assembly and the cathode production in a dry room with a dew point of  $-40^{\circ}\text{C}$ . Table 2 summarizes the basic cell- and production-specific parameters of the scenario analysis. The entire list of parameters for the materials, processes, and general economic data, including their sources, is provided in the Supplementary Tables S4–S9.

For the economic assessment, 3 main cost metrics are considered. These metrics comprise the full costs, the marginal costs, and the levelized costs. While the marginal costs indicate the cost of producing an additional unit and are particularly relevant in periods of overcapacity, the levelized costs correspond to the minimal price needed to be realized to achieve a net present value of 0 within the project duration, considering the capital costs [60,61]. Further details on these cost metrics can be found in Lechner et al. [34]. The operation time of the factory was assumed to be 10 years, aligning with the assumed depreciation period for the machines.

**Table 2**

Basic cell- and production-specific parameters considered for the scenario analysis

	Parameter	Value	Unit
Cell	Format	Cylindrical 4680	-
	Chemistry	NMC811–Graphite	-
	Capacity	26.71	Ah
	Total weight	400.25	g
	Gravimetric energy density	246.95	Wh kg <sup>-1</sup>
Production	Production capacity	15	GWh year <sup>-1</sup>
	Operating days	365	days
	Hours per shift	8	h
	Shifts per day	3	-
	Factory operation time	10	years
	Depreciation period of machines	10	years

NMC = LiNi<sub>x</sub>Mn<sub>y</sub>Co<sub>z</sub>O<sub>2</sub>

## 5.2. Modeling approach

The model architecture is based on the cost model from Lechner et al. [34] and the extension with the footprint modeling from Lechner et al. [59]. The full cost  $FC$  is divided into material cost  $C_M$ , labor cost  $C_L$ , energy cost  $C_E$ , depreciation cost  $C_D$ , building and land cost  $C_{B\&L}$ , and factory planning cost  $C_{FP}$  according to Eq. (1):

$$FC = C_M + C_L + C_E + C_D + C_{B\&L} + C_{FP} \quad (1)$$

The factory planning costs consist of 4 different cost types, which are material costs  $C_{FP,M}$ , labor costs  $C_{FP,L}$ , rental costs  $C_{FP,R}$  and energy costs  $C_{FP,E}$  as shown in Eq. (2):

$$C_{FP} = C_{FP,M} + C_{FP,L} + C_{FP,R} + C_{FP,E} \quad (2)$$

### 5.2.1. Material costs

According to Eq. (6), the material costs result from the input material  $\vec{n}_{mat,new,p}$  and the material prices  $\vec{c}_{mat}$ . The ramp-up costs are calculated weekly, as they depend on the weekly changing yield  $f_{yield,p}^i$  of the processes  $p$  and the amount of input material needed. The parameter  $f_{yield,p}^i$  is calculated according to Eq. (3). In the second part of the equation the reduction in the yield of process step  $p$  is calculated by the overall yield of the production line  $f_{yield,production,line}$ , the percentage of the yield  $f_{yield,line}^i$  in ramp-up week  $i$  of  $f_{yield,production,line}$ , and the number of processes with a yield below 100%  $n_{yield,<100\%}$ . The number of processes with a yield below 100% is needed to distribute the yield reduction evenly between them. The input material for the mixing process  $\vec{n}_{mat,new,Mixing}$  in the ramp-up week  $i$  corresponds to a percentage of the input material for the mixing process in the running production  $f_{input}^i$  and the input material during running production  $\vec{n}_{mat,Mixing}^{production}$  needed. The input material for the mixing process is equal to the material demand of this process  $\vec{n}_{mat,Mixing}^i$  as shown in Eq. (4). This allows the material demand for the following processes  $\vec{n}_{mat,p}^i$  to be calculated with Eq. (5) by considering the yield from the previous processes  $f_{yield,p-1}^i$  and the new input material  $\vec{n}_{mat,new,p}^i$ .

The parameters  $f_{input}^i$  and  $f_{yield,line}^i$  are given by the ramp-up curves that are shown in Supplementary Fig. S7 with Table S8 listing the assumed values. The ramp-up curves are defined by the user with support points and created by interpolation. The parameters  $f_{input}^i$  and  $f_{yield,line}^i$  for week  $i$  of the ramp-up are calculated by integrating the corresponding curve from week  $i-1$  to  $i$ .

$$f_{yield,p}^i = f_{yield,production,p}^i \cdot ((f_{yield,line}^i \cdot f_{yield,production,line}^i)^{1/n_{yield,<100\%}}) \quad (3)$$

$$\vec{n}_{mat,Mixing}^i = \vec{n}_{mat,new,Mixing}^i = \vec{n}_{mat,Mixing}^{production} \cdot f_{input}^i \quad (4)$$

$$\vec{n}_{mat,p}^i = \vec{n}_{mat,p-1}^i \cdot f_{yield,p-1}^i + \vec{n}_{mat,new,p}^i \quad (5)$$

$$C_{FP,M} = \sum_i \sum_p \vec{n}_{mat,new,p}^i \cdot \vec{c}_{mat} \quad (6)$$

$i \in \{\text{ramp} - \text{up week}\}$

$p \in \{\text{processes}\}$

### 5.2.2. Labor costs

As shown in Eqs. (7) and (8), labor costs are calculated by the yearly salary  $c_{year,y}$  of the 4 personnel types  $y$ , which are skilled workers, assistant workers, leadership overhead, and cleaning staff, and the duration of weeks  $d^j$  of each factory planning phase  $j$ , and the number of workers  $n_y^j$ . It must be mentioned that the necessary staff for planning the gigafactory are considered as skilled workers.

$$C_{FP,L,y}^j = n_y^j \cdot c_{year,y} \cdot d^j / 52 \quad (7)$$

$$C_{FP,L} = \sum_j \sum_y C_{FP,L,y}^j \quad (8)$$

$y \in \{\text{skilled workers, assistant workers, leadership overhead, cleaning staff}\}$

$j \in \{\text{planning of buildings and infrastructure,}$

construction of buildings and infrastructure,

planning of production,

installation and commissioning of production, ramp

– up phase 1 and 2}

### 5.2.3. Rental costs

Offices for the workers are already required for the planning of the gigafactory until the factory building is built. Rental costs for offices must therefore be taken into account. These are calculated based on the number of workers  $n_{workers}$  in the planning phase, which is the sum of the workers in these phases corresponding to Eq. (9). As shown in Eq. (10), the office size per employee  $a_{office}$ , the rental duration  $d^{rent}$ , and the monthly rent  $c_{office}$  are also needed to calculate the rental costs.

$$n_{workers} = \sum_j \sum_y n_y^j \quad (9)$$

$$C_{FP,R} = n_{workers} \cdot a_{office} \cdot c_{office} \cdot d^{rent} / 4 \quad (10)$$

$y \in \{\text{skilled workers, leadership overhead, cleaning staff}\}$

$j \in \{\text{planning of buildings and infrastructure,}$

construction of buildings and infrastructure, planning of production}

### 5.2.4. Energy costs

When calculating energy costs, a distinction must be made between the calculation of the energy consumption of the individual phases (cf. Eqs. (11)–(15)). The energy consumption for the rented office  $E_{office}$  is calculated in the same way as the rental costs. This is done by the required office space and the basic media supply  $e_{basic}$ . The electrical energy consumption during installation & commissioning  $E_{inst.\&com.,elec}$  consists of the basic media supply  $e_{basic}$  for the factory area  $A_{factory}$  and the electrical energy consumption of the machines  $e_{machines,elec}$ . The energy consumption of the machines is multiplied by an operating factor  $f_{energy}$  that considers the non-continuous operation of the machines. The gas energy consumption during installation & commissioning  $E_{inst.\&com.,gas}$  does not consider a basic media supply, because this is only electrical energy. For both, the duration of the phase  $d_{inst.\&com.}$  is needed.

The energy consumptions (electrical and gas) during the ramp-up  $E_{\text{ramp-up,elec}}$  and  $E_{\text{ramp-up,gas}}$  consider the energy consumption of the machines and the energy consumption (electrical and gas) of the production environments  $e_{\text{environment,elec}}$  and  $e_{\text{environment,gas}}$ , as well as the basic media supply. It is assumed that the production environments require half of their energy consumption in the non-productive time  $d_{\text{off}}^j$ , because of less moisture input. Finally, the energy costs  $C_{\text{FP,E}}$  result from the costs for electricity  $c_{\text{elec}}$ , and gas  $c_{\text{gas}}$ , and the corresponding consumptions as shown in Eq. (16).

$$E_{\text{office}} = n_{\text{workers}} \cdot a_{\text{office}} \cdot e_{\text{basic}} \cdot d^{\text{rent}} / 4 \quad (11)$$

$$E_{\text{inst. \& com., elec}} = (A_{\text{factory}} \cdot e_{\text{basic}} + f_{\text{energy}} \cdot e_{\text{machines, elec}}) \cdot d^{\text{inst. \& com.}} \quad (12)$$

$$E_{\text{inst. \& com., gas}} = f_{\text{energy}} \cdot e_{\text{machines, gas}} \cdot d^{\text{inst. \& com.}} \quad (13)$$

$$E_{\text{ramp-up, elec}} = \sum_j (A_{\text{factory}} \cdot e_{\text{basic}} + e_{\text{machines, elec}} + e_{\text{environment, elec}} (2 - 1/2 \cdot d_{\text{off}}^j) \cdot d^j) \quad (14)$$

$$E_{\text{ramp-up, gas}} = \sum_j (e_{\text{machines, gas}} + e_{\text{environment, gas}} (2 - 1/2 \cdot d_{\text{off}}^j) \cdot d^j) \quad (15)$$

$$C_{\text{FP,E}} = c_{\text{elec}} \cdot (E_{\text{office}} + E_{\text{inst. \& com., elec}} + E_{\text{ramp-up, elec}}) + c_{\text{gas}} \cdot (E_{\text{inst. \& com., gas}} + E_{\text{ramp-up, gas}}) \quad (16)$$

$$j \in \{\text{ramp - up phase 1, ramp - up phase 2}\}$$

### 5.3. Modeling parameters

The modeling parameters are derived from literature, expert interviews, and questionnaires. All parameters are compiled in the Supplementary and can be found in the [Supplementary Tables S4–S9](#).

### CRedit authorship contribution statement

**Maximilian Lechner:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Felix Nanz:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Felix Diller:** Investigation, Methodology, Validation. **Ruediger Daub:** Project administration, Resources, Supervision, Writing – review & editing.

### Data availability

The authors declare that all relevant data are available in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

### Declaration of Competing Interest

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

### Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used GPT-4 for spelling and grammar checks and to improve the writing style of this manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.nxener.2026.100564](https://doi.org/10.1016/j.nxener.2026.100564).

### References

- [1] J. Fleischmann, M. Hanicke, H. Evan, D. Ibrahim, S. Jautelat, M. Linder, et al. Battery 2030: resilient, sustainable, and circular, 2023.
- [2] N. Bhandari, A. Cai, K. Yuzawa, J. Zhang, V. Joshi, F. Fang, et al. Batteries: The Greenflation Challenge. New York, 2022.
- [3] G. Grandl, F. Duffner, M. Baum, M. Möhrke, X. Wu, S. Michaelis, et al. Battery Manufacturing 2030: Collaborating at Warp Speed: What it takes for equipment manufacturers to ride the coming wave of bottleneck growth, 2024.
- [4] C. Endo, T. Kaufmann, R. Schmuck, A. Thielmann, Benchmarking International Battery Policies. Karlsruhe, 2023.
- [5] Campagnon N., Pfeiffer A., Tryggestad C. Capturing the battery value-chain opportunity; 2022.
- [6] P. Kellerhoff, Northvolt verliert Milliardenauftrag von BMW (Engl.: Northvolt loses billion-euro deal from BMW), VDI Verlag GmbH, 2024, <https://www.vdi-nachrichten.com/technik/automobil/northvolt-verliert-milliardenauftrag-von-bmw/> 21 June 2024; Available from.
- [7] A. Kampker, H.H. Heimes, W. Bernhart, I. Chan, M. Frieges, H. Born, et al. Battery Monitor 2024/2025: The Value Chain between Economy and Ecology. Aachen, 2025.
- [8] T. Kaufmann, Strategiewerkzeuge aus der Praxis (Engl.: Practical Strategy Tools), Springer, Berlin, Heidelberg, 2021.
- [9] M. Porter, The five competitive forces that shape strategy, Harv. Bus. Rev. 86 (2008) 78–93.
- [10] Fraunhofer Institute for Systems and Innovation Research ISI. Interaktive Datenbanken rund um Batterien (Engl.: Interactive Databases on Batteries), December 29, 2024. Available from: <https://metamarketmonitoring.de/de/>.
- [11] F. Duffner, L. Mauler, M. Wentker, J. Leker, M. Winter, Large-scale automotive battery cell manufacturing: Analyzing strategic and operational effects on manufacturing costs, Int. J. Prod. Econ. 232 (2021) 1–19, <https://doi.org/10.1016/j.ijpe.2020.107982>.
- [12] H. Heimes, A. Kampker, B. Dorn, C. Offermanns, G. Bockey, S. Wennemar, et al. Battery Monitor 2022. 2nd ed. Aachen, 2022.
- [13] A. Kampker, H. Heimes, B. Dorn, C. Offermanns, M. Frieges, S. Wennemar, et al. Battery Monitor 2023. 3rd ed. Aachen, 2023.
- [14] S. Michaelis, J. Schüttrumpf, A. Kampker, H. Heimes, B. Dorn, S. Wennemar, et al., Roadmap Batterie-Produktionsmittel 2030, Engl.: Roadmap Battery Production Equipment 2030, VDMA Verlag GmbH, Frankfurt am Main, 2023.
- [15] E. Stears, Building the U.S. Electric Vehicle Supply Chain: What's Changed Since 2021. Available from: <https://blog.advancedenergyunited.org/building-us-ev-supply-chain-whats-changed-since-2021>. (August 07, 2025).
- [16] S. Osaka, The U.S. invested in EV battery plants. Now they may be stranded. The Washington Post 2025, 19 June 2025; Available from: <https://www.washingtonpost.com/climate-environment/2025/06/19/electric-vehicle-battery-plants-us-manufacturing/>. (August 07, 2025).
- [17] M. Hel mold, Innovatives Lieferantenmanagement (Engl.: Innovative Supplier Management), Springer Fachmedien, Wiesbaden, 2021.
- [18] International Energy Agency. Global EV Outlook 2024; 2024.
- [19] N. Bhandari, S. Shin, A. Cai, F. Fang, K. Yuzawa, G. Lee, et al. Batteries: The Greenflation Challenge II. New York, 2022.
- [20] CATL. CATL und BMW Group schließen Rahmenvereinbarung über Lieferung zylindrischer Batterien ab (Engl.: CATL and BMW Group conclude framework agreement for the supply of cylindrical batteries), 2022.
- [21] D.U. Sauer, F. Ringbeck, Batteriesysteme und deren Steuerung (Engl.: battery systems and their control), in: A. Kampker, H. Heimes (Eds.), Elektromobilität (Engl.: Electromobility), third ed., Springer, Berlin, 2024, pp. 129–152.
- [22] M. Vogel, Woher die Autohersteller ihre Batteriezellen beziehen (Engl.: Where car manufacturers source their battery cells from). Available from: <https://www.automobil-produktion.de/technologie/woher-die-autohersteller-ihre-batteriezellen-beziehen-335.html>. (December 30, 2024).
- [23] A. Stephan, T. Hettesheimer, C. Neef, T. Schmaltz, S. Link, M. Stephan, et al. Alternative Battery Technologies Roadmap 2030+. Karlsruhe; 2023.
- [24] M.A. Hannan, M.M. Hoque, A. Mohamed, A. Ayob, Review of energy storage systems for electric vehicle applications: Issues and challenges, Renew. Sustain. Energy Rev. 69 (2017) 771–789, <https://doi.org/10.1016/j.rser.2016.11.171>.
- [25] T. Schmaltz, T. Wicke, L. Weymann, P. Voß, C. Neef, A. Thielmann, Solid-State Battery Roadmap 2035+. Karlsruhe, 2022.

- [26] L.E. Hombach, L. Doré, K. Heidgen, H. Maas, T.J. Wallington, G. Walther, Economic and environmental assessment of current (2015) and future (2030) use of E-fuels in light-duty vehicles in Germany, *J. Clean. Prod.* 207 (2019) 153–162, <https://doi.org/10.1016/j.jclepro.2018.09.261>.
- [27] C. Bradley, M. Chui, K. Russell, K. Ellingrud, M. Birshan, S. ChettihThe next big arenas of competition, 2024.
- [28] T. Greitemeier, S. Lux, The intellectual property enabling gigafactory battery cell production: An in-depth analysis of international patenting trends, *J. Energy Storage* 108 (2025) 1–11, <https://doi.org/10.1016/j.est.2024.115083>.
- [29] D. Manh-Cuong, C. Kienzle, C. Rosner, A. Kampker, H. Heimes, J.F. Plumeyer, Guide to the Industrialization of Lithium-Ion Batteries in the Automotive Industry. Stuttgart, 2024.
- [30] Bernhart W., Gabaldon D., Zheng R., Schmitt P., Hotz T., Braun S. et al. Rising opportunities for battery equipment manufacturers. München; 2020.
- [31] Heimes H.H., Kampker A., Frieges M., Bockey G., Soldan Cattani N., Kisseler N. et al. Battery Atlas 2024. 2nd ed. Aachen; 2024.
- [32] J.H. Miedema, H.C. Moll, Lithium availability in the EU27 for battery-driven vehicles: the impact of recycling and substitution on the confrontation between supply and demand until 2050, *Resour. Policy* 38 (2) (2013) 204–211, <https://doi.org/10.1016/j.resourpol.2013.01.001>.
- [33] T. Greitemeier, A. Kampker, J. Tübke, S. Lux, China's hold on the lithium-ion battery supply chain: prospects for competitive growth and sovereign control, *J. Power Sources Adv.* 32 (2025) 1–7, <https://doi.org/10.1016/j.powera.2025.100173>.
- [34] M. Lechner, A. Kollenda, K. Bendzuck, J.K. Burmeister, K. Mahin, J. Keilhofer, L. Kemmer, M.J. Blaschke, G. Friedl, R. Daub, A. Kwade, Cost modeling for the GWh-scale production of modern lithium-ion battery cells, *Commun. Eng.* 3 (1) (2024) 1–11, <https://doi.org/10.1038/s44172-024-00306-0>.
- [35] E1 PropTec Solutions Management UG. Standortanalyse Shanghai, February 26, 2025. Available from: <https://www.e1-holding.com/standortanalyse-shanghai/>.
- [36] onvista. Chinesischer Renminbi Yuan in US Dollar - Aktueller Kurs CNY/USD - Wechselkurs - onvista (Engl.: Chinese Renminbi Yuan to US Dollar - Current exchange rate CNY/USD - Exchange rate - onvista), February 26, 2025; Available from: <https://www.onvista.de/devisen/Chinesischer-Renminbi-Yuan-US-Dollar-CNY-USD>.
- [37] onvista. Euro in US Dollar - Aktueller Kurs EUR/USD - Wechselkurs - onvista (Engl.: Euro to US Dollar - Current EUR/USD exchange rate - onvista), February 25, 2025. Available from: <https://www.onvista.de/devisen/Eurokurs-Euro-Dollar-EUR-USD>.
- [38] LoopNet. Ontario Office Space for Lease | LoopNet, February 26, 2025. Available from: <https://www.loopnet.com/search/office-space/on-canada/for-lease/?sk=ee82103d3d5ff0f33f682ae0069b4508>.
- [39] LoopNet. Phoenix, AZ Office Space for Lease | LoopNet, February 26, 2025. Available from: <https://www.loopnet.com/search/office-space/phoenix-az/for-lease/?sk=6b1256e73a717d9dd78a5ee1e442a5e4>.
- [40] PwC. China, People's Republic of - Corporate - Taxes on corporate income, November 24, 2024. Available from: <https://taxsummaries.pwc.com/peoples-republic-of-china/corporate/taxes-on-corporate-income>.
- [41] M. Schölles, Internationaler Energiepreisvergleich für die Industrie (Engl.: International Energy Price Comparison for Industry). München, 2023.
- [42] Turner & Townsend. International construction market survey, 2024.
- [43] Arcadis. International Construction Costs 2024, 2024.
- [44] Eurostat. Preise Gas für Nichthaushaltskunde, ab 2007 - halbjährliche Daten (Engl.: Gas prices for non-household customers, from 2007 - half-yearly data), December 26, 2024. Available from: [https://ec.europa.eu/eurostat/databrowser/view/nrg\\_pc\\_203\\$defaultview/default/table](https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_203$defaultview/default/table).
- [45] Eurostat. Preise Elektrizität für Nichthaushaltskunde, ab 2007 - halbjährliche Daten (Engl.: Electricity prices for non-household customers, from 2007 - half-yearly data), December 26, 2024. Available from: [https://ec.europa.eu/eurostat/databrowser/view/nrg\\_pc\\_203\\$defaultview/default/table](https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_203$defaultview/default/table).
- [46] Statistische Bundesamt. Kauffälle, Veräußerte Fläche, Kaufsumme, Durchschnittlicher Kaufwert für Bauland: Deutschland, Quartale, Art der Baufläche, Art des Grundstücks (Engl.: Purchase cases, area sold, purchase price, average purchase value for building land: Germany, quarters, type of building area, type of property), December 30, 2024. Available from: <https://www-genesis.destatis.de/datenbank/online/statistic/61511/table/61511-0001>.
- [47] I.G. Metall. Tarif tabellen Metall- und Elektroindustrie: Monatsentgelte (Engl.: Tarif tables for the metal and electrical industry: monthly), 2024.
- [48] I.G. Metall. Tarif tabellen Metall- und Elektroindustrie: Monatsentgelte (Engl.: Tarif tables for the metal and electrical industry: monthly); 2018.
- [49] Fischer D., Stephan N., Wellstein A. Makro Research Immobilien Sektor Büromärkte global, February 26, 2025. Available from: [https://deka.de/site/dekade\\_deka-gruppe\\_site/get/documents/dekade/Publikationen/2024/Immobilien/20240704\\_Bueroemaerkte\\_global.pdf](https://deka.de/site/dekade_deka-gruppe_site/get/documents/dekade/Publikationen/2024/Immobilien/20240704_Bueroemaerkte_global.pdf).
- [50] K. Knazler, M. Preuß, M. Angersbach, A. Waldmann, Büromarkt Frankfurt am Main 2023 (Engl.: Office market Frankfurt am Main 2023), 2023.
- [51] C. Schröder, Industrielle Arbeitskosten im internationalen Vergleich (Engl.: Industrial Labor Costs in International Comparison), *IWTrends Vierteljahresschr. Zur. Empir. Wirtsch.* 46 (2019) 63–81, <https://doi.org/10.2373/1864-810X.19-02-05>.
- [52] Bundesministerium der Finanzen. Die wichtigsten Steuern im internationalen Vergleich 2023 (Engl.: International Comparison of The Most Important Taxes in 2023). 2024th ed. Berlin, 2024.
- [53] F. Degen, O. Krätzig, Modeling large-scale manufacturing of lithium-ion battery cells: impact of new technologies on production economics, *IEEE Trans. Eng. Manag.* 71 (2023) 6753–6769, <https://doi.org/10.1109/TEM.2023.3264294>.
- [54] ElevenFlo. Northvolt: \$100M Scania DIP and Asset Sales Update, February 15, 2026. Available from: <https://elevenflo.com/blog/northvolt-bankruptcy>.
- [55] The White House. FACT SHEET: President Biden Takes Action to Protect American Workers and Businesses from China's Unfair Trade Practices, December 25, 2024. Available from: <https://www.whitehouse.gov/briefing-room/statements-releases/2024/05/14/fact-sheet-president-biden-takes-action-to-protect-american-workers-and-businesses-from-chinas-unfair-trade-practices/>.
- [56] S. Haghi, J. Keilhofer, N. Schwarz, P. He, R. Daub, Efficient analysis of interdependencies in electrode manufacturing through joint application of design of experiments and explainable machine learning, *Batter. Supercaps* 7 (2023) 1–18, <https://doi.org/10.1002/batt.202300457>.
- [57] S. Stock, S. Pohlmann, F.J. Günter, L. Hille, J. Hagemeyer, G. Reinhart, Early quality classification and prediction of battery cycle life in production using machine learning, *J. Energy Storage* 50 (2022) 1–12, <https://doi.org/10.1016/j.est.2022.104144>.
- [58] A. Sommer, S. Bazlen, H.-Y. Tran, M. Leeb, J. Wachter, W. Braunwarth, et al., Integration of an electrode-sheet-based traceability system into the manufacturing process of lithium-ion battery cells, *Energy Tech.* 12 (2024) 1, <https://doi.org/10.1002/ente.202301221>.
- [59] M. Lechner, F. Nanz, J. Keilhofer, A. Kollenda, R. Daub, Cost model for the footprint planning of production environments in lithium-ion battery production, *Energy Tech.* 13 (3) (2025) 1–16, <https://doi.org/10.1002/ente.202402311>.
- [60] S. Reichelstein, A. Rohlfing-Bastian, Levelized product cost: concept and decision relevance, *Account. Rev.* 90 (4) (2015) 1653–1682, <https://doi.org/10.2308/accr-51009>.
- [61] G. Friedl, C. Hofmann, B. Pedell, *Kostenrechnung - Eine entscheidungsorientierte Einführung* (Engl.: Cost Accounting - A Decision-Oriented Introduction), fourth ed., Verlag Franz Vahlen, München, 2022.