Supplementary information for: Cost, volumetric energy density, and fast-charging projections of Na-ion and Li-ion batteries from a European perspective

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1 Cost modelling

The following section begins by outlining the relevant parameters for the cost modelling, with a focus on labor, energy, and other manufacturing-related cost factors. This is followed by a description of the raw material cost modelling and the introduction of regional differences. As a first step, however, we present the currency exchange rate table, as many of the underlying data sources report values in different currencies. To ensure consistency, all cost values are converted and presented in euros (EUR).

Table 1: Currency exchange rates for 2024 based on [1], rounded to four decimal digits

Currency exchange/year	2024
CNY in EUR	0.1287
USD in EUR	0.9243
SEK in EUR	0.0874
NOK in EUR	0.0859

1.1 Labour, energy and other cost parameters

The labor, energy, and other region-specific cost parameters are listed in the table below. A distinction is made between China and countries in the European region.

Table 2: Labor, energy and other cost parameters for the investigated regions and countries

Parameter	Region	Country	Subregion	Value	Unit	Data period [-]	Source [-]	Comment [-]
Electricity cost	Asia	China	Inner Mongolia	0.0589	EUR kWh^{-1}	2024	[2]	Hohhot as the capital taken as representative for inner Mongolia Applied for SG, NG, HC, LFP, NFM and NCZNMT production
Electricity cost	Asia	China	Rest of China	0.0952	EUR kWh^{-1}	2024	[3]	Changsha as a highly industrialized city taken as representative for the rest of China Applied for battery cell production
Electricity cost	Europe	Norway	-	0.0354	EUR kWh^{-1}	2024	[4]	Average of quarterly values for 2024, for energy intensive manufacturing Applied for SG production
Electricity cost	Europe	Spain	-	0.1043	EUR kWh^{-1}	2024	[5]	Applied for battery cell production
Gas price	Europe	Spain	-	0.0575	EUR kWh^{-1}	2024	[6]	Applied for battery cell production

Building cost	Europe	Spain	-	1200.00	EUR m^{-2}	2024	[7]	Applied for battery cell production
Electricity cost	Europe	Sweden	-	0.0579	EUR kWh^{-1}	2024	[8]	Average of 2024H1 and 2024H2 for non-household 500-1999 MWh per year Applied for NG production
Electricity cost	Europe	Finland	-	0.0557	EUR kWh^{-1}	2024	[9]	Applied for HC production
Electricity cost	Europe	Hungary	-	0.1640	EUR kWh^{-1}	2024	[10]	Applied for NFM and NCZNMT production
Labour cost	Asia	China	-	6.3334	EUR h^{-1}	2024	[11]	Calculated based on average wages in China per year divided by average working hours per year
Labour cost	Europe	Norway	-	46.24	EUR h^{-1}	2024	[12]	Average labour costs per full-time equivalent employee for all industries, data only available until 2023. Therefore, value for 2024 interpolated based on 2023 value and average salary growth over the last five years
Labour cost	Europe	Sweden	-	40.3	EUR h^{-1}	2024	[13]	-
Labour cost	Europe	Finland	-	37.7	EUR h^{-1}	2024	[13]	-
Labour cost	Europe	Hungary	-	14.1	EUR h^{-1}	2024	[13]	-
Full time employee (FTE) working hours	Asia	China	-	2285	h $year^{-1}$	2024	[14]	Based on 48.0 h/week, assuming 10 holiday days (annual leave depends on employment duration and ranges between 5-15 days), 13 public holiday days (on working days) and 104 weekend days

FTE working hours	Europe	Spain	-	1777	h year^{-1}	2024	[15]	Based on 40.2 h/week, assuming 30 holiday days (common), 10 public holiday days (on working days) and 104 weekend days
FTE working hours	Europe	Norway	-	1658	h year^{-1}	2024	[16]	Based on 37.5 h/week, assuming 30 days of holiday (common), 10 public holiday days (on working days) and 104 weekend days
FTE working hours	Europe	Sweden	-	1805	h year^{-1}	2024	[15]	Based on 41.4 h/week, assuming 30 days of holiday (common), 13 public holiday days (on working days) and 104 weekend days
FTE working hours	Europe	Finland	-	1716	h year^{-1}	2024	[15]	Based on 39.0 h/week, assuming 30 days of holiday (common), 11 public holiday days (on working days) and 104 weekend days
FTE working hours	Europe	Hungary	-	1862	h year^{-1}	2024	[15]	Based on 40.3 h/week, assuming 20 days of holiday (common), 11 public holiday days (on working days) and 104 weekend days

1.2 Raw materials

To determine the costs of raw and auxiliary materials, we use average raw material prices representative of the 2024 price level. The main data sources are the Shanghai Metals Market (SMM) [17] and Fastmarkets [18]. To account for uncertainties and volatility in future raw material prices, we include a sensitivity analysis in the main text of the key cost drivers. Since the raw material data originates from various local currencies, all values were converted to EUR using the average 2024 exchange rates.

1.2.1 Calculation of regional differences

The determination of regional differences in raw material costs between Europe and China forms the basis for the region-specific analysis. The objective is to identify these differences by analyzing historical data for key battery raw materials - such as lithium and nickel - and to derive a trend indicating by what percentage raw material costs in Europe can generally be expected to differ from those in China. This includes identifying cases where certain materials may be more affordable in Europe. The analysis focuses on the most cost-intensive raw materials used in battery production. Regional cost differences for metals are calculated based on data from Fastmarkets according to the following logic:

$$Regional\ raw\ material\ price = \ base\ price + regional\ premium\ or\ surcharge$$

The base price is obtained from commodity exchanges such as the LME, CME/COMEX, or SHFE (for China) and is adjusted by adding the respective regional premium or surcharge. This approach was applied to several metal – Li_2CO_3 is analyzed as an example. The analysis showed that, on average, raw material costs differ by approximately 10 % between Europe and China, with costs being higher in Europe. For European raw materials, for which no region-specific price data were available, this 10 % regional difference was applied as a flat-rate surcharge. This assumption covers both imported and domestically produced raw materials. Although most battery-relevant raw materials are mined and processed in China, local production in Europe would need to match import prices to remain competitive, as otherwise imports would be economically preferable.

A limitation of this approach is that the analysis is based on exchange-listed prices rather than long-term supply contracts, for which no reliable data is currently available. Such contracts may result in price differences not captured in this analysis.

1.2.2 Lithium carbonate

For key battery raw materials such as lithium, it is essential to highlight regional price differences. Therefore, the comparison is based on the spot prices for battery-grade lithium carbonate (Li_2CO_3 - LCE) on the European and Chinese markets. The Chinese market provides daily spot prices, while the European market reports weekly quotations. As both markets publish prices as ranges, the mid-point values were used in this analysis. All data were sourced from Fastmarkets [19], and values originally reported in RMB or USD were converted to EUR using the corresponding average 2024 exchange rates. This results in 12.25 EUR kg^{-1} for Europe and 10.96 EUR kg^{-1} for China in 2024.

Table 3: Price data for LCE for different scenarios

Scenario	China LCE [EUR kg^{-1}]	Europe LCE [EUR kg^{-1}]	Source
Baseline (2024)	10.96	12.25	Fastmarkets

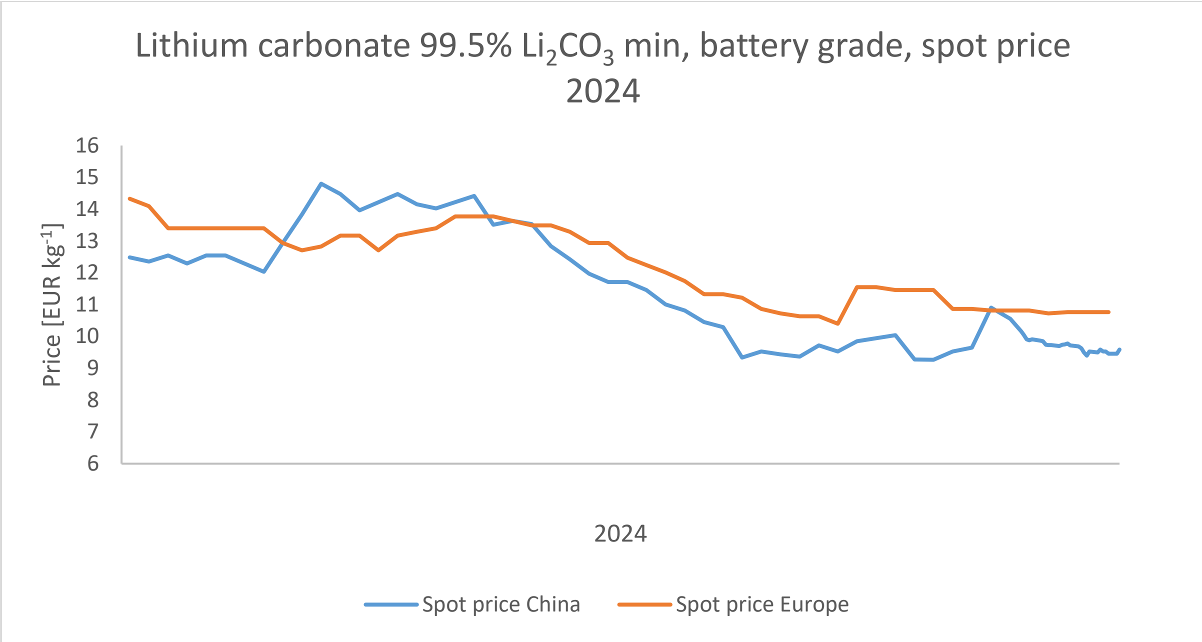

Figure 1: Spot price comparison between LCE in China and Europe for 2024

1.2.3 Graphite

For graphite costs, the costs of the precursor, in the case of NG flake graphite and in the case of AG green petroleum coke and petroleum needle coke are analyzed. We utilize the current market price from [18] for flake graphite, which is 479 USD t^{-1} for China and 657 USD t^{-1} for the EU on average in 2024. This equals 0.44 EUR kg^{-1} for China and 0.61 EUR kg^{-1} for the EU.

Table 4: Price data for flake graphite for different scenarios

Scenario	**China flake 94% C -100 mesh [EUR kg^{-1}]**	**Europe flake 94% C -100 mesh [EUR kg^{-1}]**	**Source**
Baseline (2024)	0.44	0.61	Fastmarkets

Table 5: Price data for petroleum needle coke for different scenarios

Scenario	**China petroleum needle coke 0.5 % S [EUR kg^{-1}]**	**Europe petroleum needle coke 0.5 % S [EUR kg^{-1}]**	**Source**
Baseline (2024)	0.66	0.73	Fastmarkets

Table 6: Price data for green petroleum coke for different scenarios

Scenario	**China green petroleum coke 0.5 % S [EUR kg^{-1}]**	**Europe green petroleum coke 0.5 % S [EUR kg^{-1}]**	**Source**
Baseline (2024)	0.33	0.37	Fastmarkets

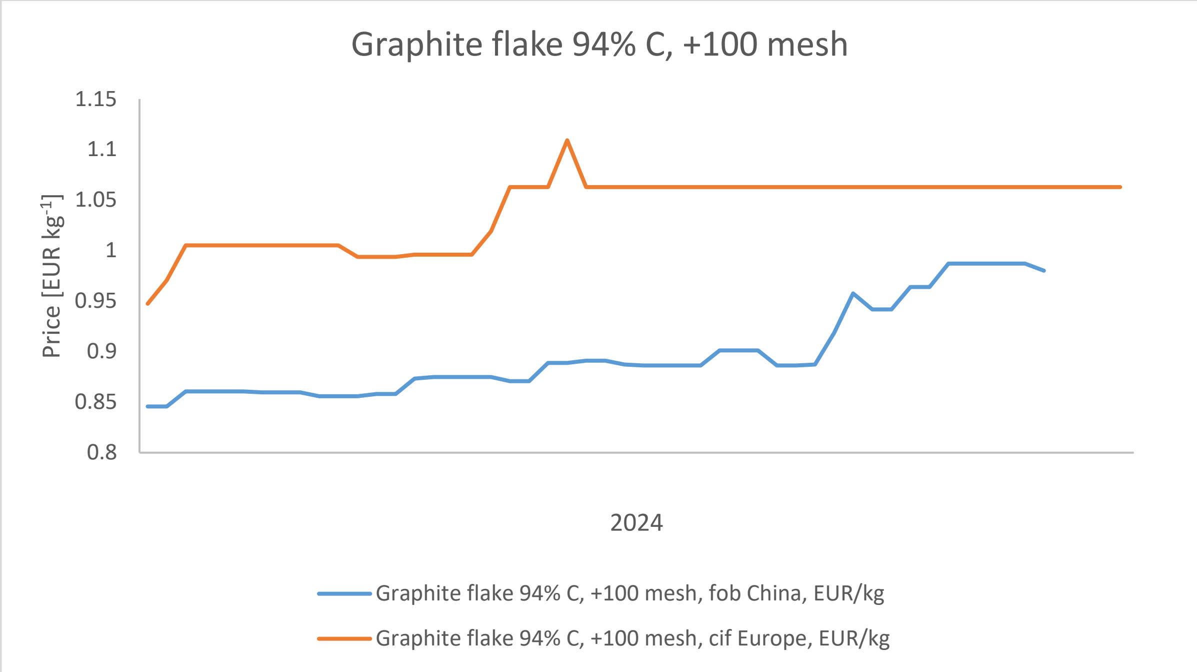

Figure 2: Spot price comparison between flake graphite in China and Europe for 2024

1.2.4 Nickel

For nickel, we use price data from SMM. We assume the use of nickel oxide (NiO), as it is more cost-effective in precursor-free synthesis routes and increasingly favored by developers of single-crystal layered oxides. In 2024, the average NiO price in China reported by SMM was 14.57 EUR kg^{-1}. Applying the previously observed 10 % surcharge for European production results in a price of 16.03 EUR kg^{-1} for Europe.

Table 7: Price data for NiO for different scenarios

Scenario	China NiO [EUR kg^{-1}]	Europe NiO [EUR kg^{-1}]	Source
Baseline (2024)	14.57	16.03	SMM

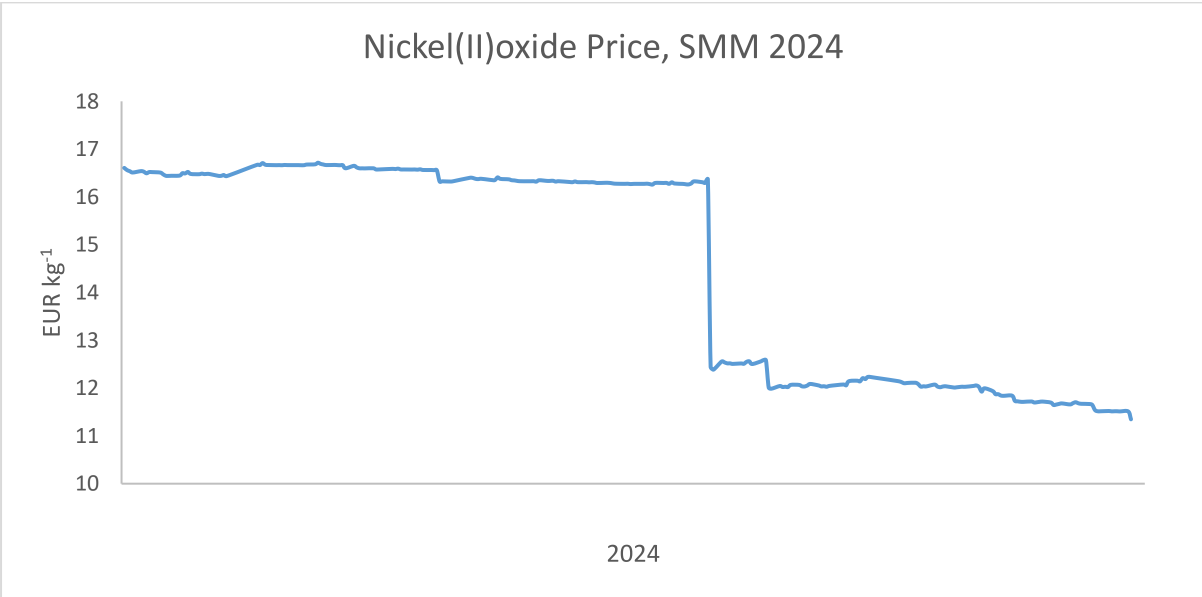

Figure 3: NiO price for China in 2024 based on SMM

1.2.5 Copper and aluminum

The following section presents the cost calculations for copper and aluminum. As discussed previously, the total cost is determined by adding a regional premium or surcharge to the base price. It should be noted that this premium can also be negative, indicating that domestic production is more cost-effective than imports. In such cases, importing the metal would be economically disadvantageous.

Table 8: Price data for copper for different scenarios

Scenario	China Copper [EUR kg^{-1}]	Europe Copper [EUR kg^{-1}]	Source
Baseline (2024) incl. premium	8.78	8.86	Fastmarkets

Table 9: Price data for aluminum for different scenarios

Scenario	China Aluminum [EUR kg^{-1}]	Europe Aluminum [EUR kg^{-1}]	Source
Baseline (2024) incl. premium	2.60	2.74	Fastmarkets

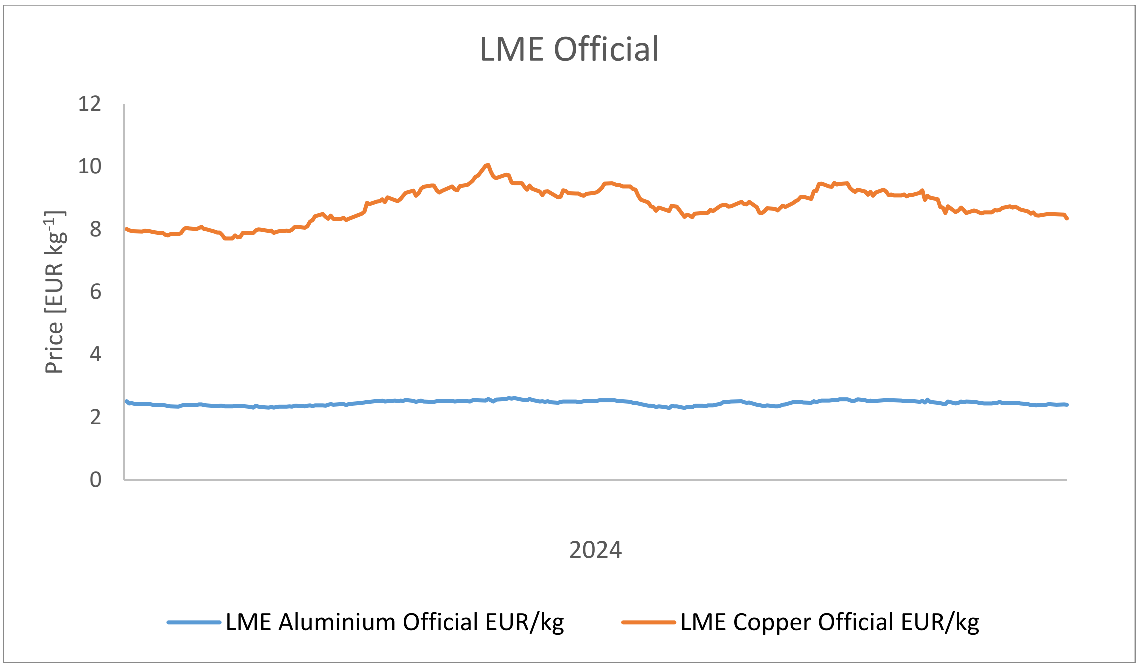

Figure 4: Copper and aluminum price in 2024 based on LME

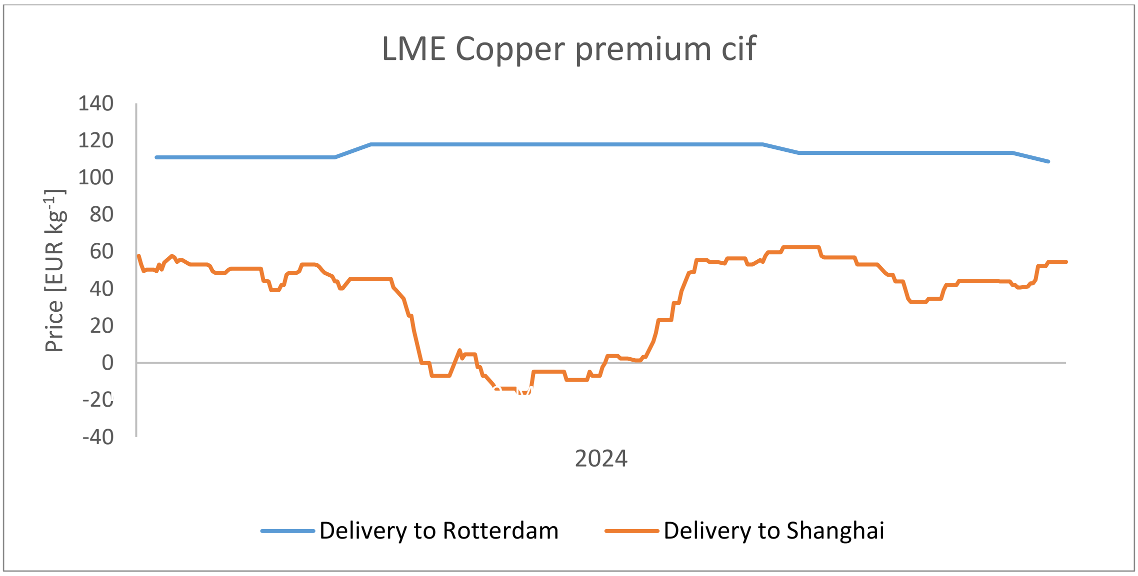

Figure 5: LME copper premium cif

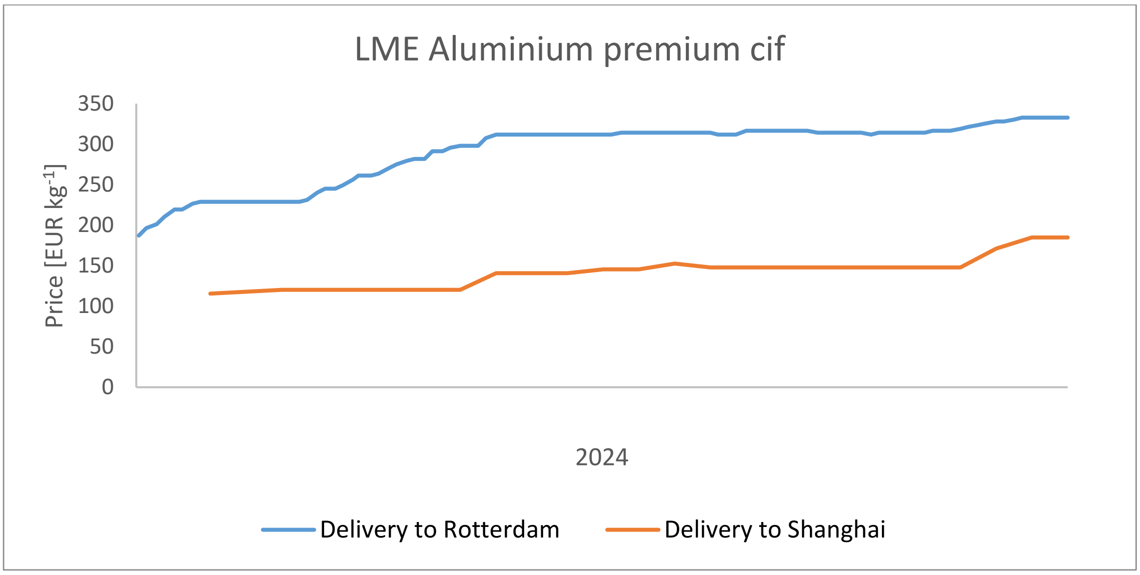

Figure 6: LME aluminium premium cif

1.2.6 Other

As previously highlighted, analysis of historical data showed that raw material costs in Europe are approx. 10 % higher than in China. Therefore, for all materials where no region-specific cost data outside of China are available, we assume a 10 % cost increase for Europe.

Table 10: Raw material cost overview for positive and negative electrode and battery cell production

Raw material	Cost China [USD/mt]	Cost China [EUR/kg]	Cost Europe [EUR/kg]	Data period [-]	Source [-]
Positive electrode					
Mn_3O_4	1,545.94	1.43	1.57	2024	SMM, Mn3O4 (Battery-Grade) (Weekly) Price, USD/mt
Fe_2O_3	811.42	0.75	0.83	2024	SMM, Iron Oxide Red Price, USD/mt
Na_2CO_3	631.20	0.58	0.64	2024	SMM, Battery-grade Sodium Carbonate Price, USD/mt
$FePO_4$	1,287.46	1.19	1.31	2024	SMM, Iron Phosphate Price, USD/mt

ZnO		2.52	2.77	2024	SMM, Zinc Oxide Price, USD/mt
Ca		7.99	8.79	2024	SMM, Calcium 99% Price, USD/mt
Cu	see above	see above	see above	see above	
Ti		5.56	6.11	2024	SMM, Grade 0 Sponge Titanium Price, USD/mt
Negative electrode					
Coal tar pitch	561.96	0.52	0.57	2024	SMM, Coal tar pitch (Hebei) Price, USD/mt
Un-calcinated petroleum coke	340.69	0.31	0.35	2024	SMM, Low-Sulphur Petroleum Coke Price, USD/mt
Calcinated petroleum coke	495.77	0.46	0.50	2024	SMM, Low-Sulphur Calcined Petroleum Coke (North-East China) Price, USD/mt
Un-calcinated oil-based needle coke	601.41	0.56	0.61	2024	SMM, Oil-Based Green Needle Coke Price, USD/mt
Flake graphite	382.15	0.35	0.39	2024	SMM, Flake Graphite (Nationwide Average Price)(-194) Price, USD/mt
Flake graphite	457.49	0.42	0.47	2024	SMM, Flake Graphite (Nationwide Average Price)(-195) Price, USD/mt
Coconut shells	460	0.43	0.47	-	Based on UN Comtrade data [20] for imports of “Wood, charcoal of nut or shell, whether or not agglomerated” from all exporting countries, the value per unit mass was calculated by dividing the total import value by the total imported mass. The resulting unit values were then averaged to obtain a mean price.
Phenolic resin	3,454.17	3.19	2.05		Business analytiq [21], Phenolic resin price index
Coatings					
Glucose		0.69	0.76	2024	https://agridata.ec.europa.eu/extensions/DashboardSugar/SugarPrice.html#
Aluminium oxide (Al_2O_3)		0.45	0.50	2024	Aluminum oxide (Alumina) price index – businessanalytiq [21]
Coal tar pitch	see above	see above	see above	see above	
Phenolic resin	see above	see above	see above	see above	
Auxiliary materials					
Freshwater	0.67	0.00	0.01	-	Value for China taken from [22]
N-Methyl-2-pyrrolidone (NMP)	1,450.19	1.34	1.47	2024	SMM, NMP Price, USD/mt
NMP processing fee	168.33	0.16	0.17	2024	SMM, NMP Processing Fees (Excluding Packaging and Transportation Costs) Price, USD/mt
Sulfuric acid (H_2SO_4)	40.00	0.04	0.10	2024	Business analytiq [21], Sulfuric Acid price index
Chlorine	340.00	0.31	0.32	2024	Chlorine price index – businessanalytiq [21]
HF	1,531.67	1.42	-	2024	Hydrofluoric Acid price index – businessanalytiq [21]
HCl	25.00	0.02	-	2024	Hydrochloric Acid price index – businessanalytiq [21]
Binder					
PVDF	7,481.59	6.92	7.61	2024	SMM, Lithium Battery-Grade PVDF (Domestic Emulsion Method) Price, USD/mt
CMC	-	4.11	4.52	2024	SMM, Domestic CMC Price, USD/kg
SBR	-	4.93	5.42	2024	SMM, Domestic SBR Price, USD/kg

Additives					
Carbon Black (SP)	-	3.58	3.94	2024	SMM, SP Price, USD/kg
MW-CNT	-	-	-	-	Cannot be disclosed
SW-CNT	-	-	-	-	Cannot be disclosed
Current collector					
High-grade Aluminium	-	2.60	2.74	2024	Modelled as described in sections below
High-grade Copper	-	8.78	8.86	2024	Modelled as described in sections below
Copper Foil Processing Fee 4.5µm	4,051.37	3.74	3.74	2024	SMM, Lithium Battery Copper Foil Processing Fee 4.5µm (weekly) Price, USD/mt
Copper Foil Processing Fee 6µm	2,126.42	1.97	1.97	2024	SMM, Lithium Battery Copper Foil Processing Fee 6µm (weekly) Price, USD/mt
Copper Foil Processing Fee 8µm	2,018.63	1.87	1.87	2024	SMM, Lithium Battery Copper Foil Processing Fee 8µm (weekly) Price, USD/mt
Aluminum Foil Processing Fee 10µm	-	2.00	2.00	2024	Derived from correlation analysis with 15,13, and 12 µm Al-foil processing fee
Aluminum Foil Processing Fee 12µm	2,027.65	1.87	1.87	2024	SMM, Lithium Battery Aluminum Foil Processing Fee 12µ (weekly) Price, USD/mt
Aluminum Foil Processing Fee 13µm	1,905.06	1.76	1.76	2024	SMM, Lithium Battery Aluminum Foil Processing Fee 13µ (weekly) Price, USD/mt
Aluminum Foil Processing Fee 15µm	1,782.47	1.65	1.65	2024	SMM, Lithium Battery Aluminum Foil Processing Fee 15µ (weekly) Price, USD/mt
Separator					
Coated separator		0.22 [EUR/m^2]	0.24 [EUR/m^2]	2024	SMM, Wet-process Ceramic Coated Separator 7µm+2µm+1µm+1µm Price, USD/m^2
NIB separator	-	-	-	-	Cannot be disclosed
Electrolyte					
Electrolyte LIB	calculated	calculated	calculated	2024	Calculated as described in sections below
Electrolyte NIB	calculated	calculated	calculated	2024	Calculated as described in sections below
Electrolyte conducting salt					
$NaPF_6$		2.40	3.12	-	Following the logic of Yao et al. [23]. We assume that producing the electrolyte salt in Europe being ~ 30 % more expensive, rather than 10 % as for the raw materials, with the details given in the sections below.
$LiPF_6$		7.10	9.20	2024	SMM, LiPF6 Price, USD/kg
NaFSI		15.49	20.14		SMM, NaFSI Price, USD/mt, only data from 01.01.-24.09.2025 available
Electrolyte solvents					
Propylene Carbonate (PC)	1,106.49	1.02	1.12	2024	SMM, Propylene Carbonate PC（Battery-Grade，Delivery-to-Factory Price） Price, USD/mt
Ethyl Methyl Carbonate EMC	1,008.68	0.93	1.02	2024	SMM, Ethyl Methyl Carbonate EMC（Battery-Grade，Delivery-to-Factory Price） Price, USD/mt

Diethyl Carbonate DEC	1,242.65	1.15	1.27	2024	SMM, Diethyl Carbonate DEC（Battery-Grade，Delivery-to-Factory Price） Price, USD/mt

1.3 Active material production

1.3.1 Artificial graphite

The cost model for artificial graphite (AG) is based on the information provided in [24]. In the study, AG production is modelled as the transformation of calcined needle coke (a type of petroleum coke) via shaping, graphitization, and coating. The original regional scope includes China and the United States.

In this study, several adaptations and extensions are made. First, the geographical scope is expanded to include AG production in Europe. For this purpose, Norway is modelled as the representative European production location, given the presence of existing industrial capacities and favorable energy conditions. For China, AG production is modelled in the Inner Mongolia region, where low electricity prices - driven by a high share of renewable energy - make it the primary location for graphitization activities. The capital investment costs for AG production facilities and equipment in Norway are assumed to be identical to those of the United States. Capital costs reported in USD are converted into EUR using the 2024 exchange rate.

Further adjustments are made with respect to feedstock selection, following the observations in [25]:

- **High-end AG:** produced from un-calcined oil-based needle coke, using an Acheson furnace. The yield is slightly lower than that of mid-end AG.
- **Mid-end AG:** produced from un-calcined petroleum coke. An Acheson furnace is used for graphitization. Additionally, the yield is slightly lower compared to the low-end AG.
- **Low-end AG:** produced from un-calcined petroleum coke. Furthermore, the coating step is removed. Additionally, the yield is slightly higher, and different equipment is used for graphitization - specifically, a box-type furnace. According to [24], this requires an extended graphitization duration of 30-35 days (720-875 h), due to the inherently poorer thermal uniformity of the furnace design, which necessitates additional time for temperature soaking. This is significantly longer than the previous 500 h typical for Acheson furnaces. By eliminating the need for packing material and crucibles, box furnaces can save approximately 700 EUR ton^{-1} in costs. Additionally, they require about 40 % less electricity and achieve 10 % higher throughput, as the removal of packing material allows for more effective utilization of furnace volume despite the longer graphitization time

All plants are assumed to operate with a nominal capacity of 45 kt $year^{-1}$ and a 90 % operating rate. A yield of 80 % is assumed for the spheroidization process, and the internal rate of return (IRR) is set to 5 % across all configurations.

1.3.2 Natural graphite

The cost model natural graphite (NG) is based on the information provided in [24], too. NG production involves shaping of mined graphite concentrate, followed by purification and coating. As with AG, the scope of analysis is extended to include NG production in Europe. For this purpose, an NG production site in Sweden is modeled. Sweden has natural graphite reserves and existing production capacities in this area, making it a representative choice [26]. Furthermore, it is assumed that, like the US, NG production in Europe does not use the HF purification process applied in China but instead employs carbochlorination [24]. The carbochlorination process is characterized by higher investment costs. It is also assumed that investment costs for production facilities and equipment in Sweden are identical to those in the US. For investment costs originally in USD, conversion to EUR was performed using the 2024 exchange rate. Additionally, adjustments were made based on raw material demand for the acid leaching step, following Engels et al. [27].

Furthermore, the following adjustments to [24] were made: we set the IRR to 5 %, and the yield of the spherization step was increased from the initial 50 % to 80 %. In addition, the costs for HF, HCl, HNO_3, etc., were updated to reflect current 2024 values.

- **High-end NG:** requires an additional graphitization step like AG production, which results in significant additional costs. Furthermore, a higher grade of flake graphite is used as a feedstock.
- **Mid-end NG:** A higher grade of flake graphite is used as a feedstock, but no additional graphitization.
- **Low-end NG:** The coating step is removed, a lower type of flake graphite assumed, and the yield of the overall process is higher.

1.3.3 Hard carbon

Next, the production of HC is described and modeled. In our analysis, HCs derived from three different precursor types are considered, including coconut shell-based HC, pitch-based HC, and resin-based HC. The following section focuses on coconut shell-derived HC which serves as the baseline for the other HC types.

1.3.3.1 Coconut shell-based HC

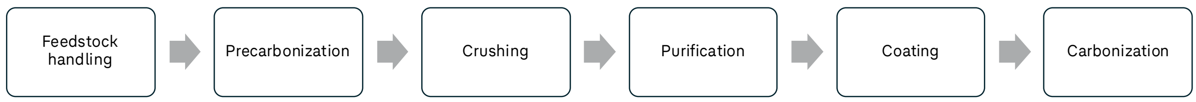

Figure 7: Production process of coconut-based HC primarily based on [28] and industrial data

The first step is feedstock handling. In this study, the costs are based on [29], where a pretreatment cost of 80 USD per dry ton of biomass blendstock is assumed, covering procurement, preprocessing, and delivery to the plant gate. This includes the capital and energy requirements for drying the biomass to 10 % moisture content and reducing the particle size to 2 mm. To ensure stable moisture levels during the wet season, an additional dryer and flue-gas blower are included in the system design. This corresponds to a feedstock handling cost of 0.08 USD kg^{-1}. As the cost data refers to 2024, values are converted to euros using the 2024 exchange rate, resulting in 0.07 EUR kg^{-1} for Europe. Applying the regional cost factor of 0.61 from EverBatt [30], a handling cost of 0.04 EUR kg^{-1} is assumed for China. For subsequent life cycle assessment, the associated energy demand is 400 kW for a throughput of 2,000 t day^{-1} of dry biomass, corresponding to 4.8 kWh t^{-1}, which is comparatively low.

The second step is precarbonization. For this, information from Liu et al. [31] on industrial HC production from bamboo is primarily used. They report a dry mass throughput of 3673 kg biomass with a pyrolysis duration of 2.79 h, which corresponds to an annual throughput of 11.54 kt $year^{-1}$. The electricity demand of the process is calculated as 326 kWh t^{-1}. For labor, it is assumed that the precarbonization process also requires 8 FTE, as for the spheronization process in natural graphite production based on [24]. The need for an inert gas in this process step is given by Liu et al. [31] as 0.06 kg kg HC^{-1}. While argon is used in the reference study, nitrogen is more commonly applied in industrial practice and is therefore assumed in this work. The machines for the precarbonization line include a rotary kiln, bucket elevator, screw feeder, feed bin, waste heat boiler, cooling, etc., and further auxiliary equipment. The baseline for the design is an industrial line from activated carbon production [32]. The costs for the respective equipment were calculated using the methodology described in [30], with the current CPCI for August 2025 and converted into EUR using the average exchange rate of 2024. The CAPEX including installation, piping, etc., amounts to 6,273,000 EUR in China and 10,283,000 EUR in Finland per line.

Next, the crushing process is considered in the model, with a baseline throughput of 6 t h^{-1}. The electricity demand of the process is given by Liu et al. [31] as 346 kWh/t. The FTE requirement per crushing line is assumed to be 3. The machines in a line include a hammer mill (primary crusher), a ball mill (secondary crusher), a vibrating screen, and a conveyor belt. The investment costs amount to 495,000 EUR in China and 811,000 EUR per line in Finland based on the methodology described above.

Next, the purification step is modeled. It should be noted that this process is challenging to represent, as purification is frequently outsourced by HC suppliers, resulting in limited publicly available data. The raw material requirements for HC from bamboo are given in [31] as: 10.43 tonnes H_2O per tonne HC, 3.56 t sulfuric acid (H_2SO_4), and 0.33 tonnes N_2 per tonne HC. We assume that it is the same for HC from coconut shells. However, further information on industrial production of this step needs to be found, especially regarding the different biomass-based precursors. To address this, various publications on activated carbon production are consulted. For example, [33] describes purification of activated carbon using phosphoric acid and the associated equipment. Overall, the costs for a line that can activate 8,000 kg pecan shells per day are given as 6,324,000 USD for 2003. Converted to 2024 values in EUR, this results in an investment of 10,239,000 EUR for a line in Finland and 6,245,790 EUR for China, with a capacity of 2.56 kt year^{-1}. To determine throughput, the purification duration is needed. For this, information from Dou et al. [34] is used, who describe the relationship between purification duration and HC performance. They conclude that two weeks of acid treatment lead to the best performance. However, Liu et al. [31] describe 16 h for bamboo, so this is assumed here for coconuts, too. This results in a throughput of 0.16 t h^{-1}. [33] also states that 70 % of the sulfuric acid can be recovered. Accordingly, the investment for H_2SO_4 is included in CAPEX, and for OPEX, only 30 % is calculated for the acid. For FTE calculation, [33] specifies 3 persons per shift, with three shifts per day, a wage of 18 USD h^{-1}, and 320 working days per year. Converting with 2,080 h per FTE per year results in approx. 13 FTE per line.

For HC coating, it is assumed that this is analogous to coating NG and AG in terms of equipment, energy consumption, and FTE [24]. We also assume a pitch-based coating but point out that there are different variants discussed in literature such as also using an Al_2O_3 or resin-based coating.

For carbonization, Liu et al. [31] is again referenced. In their study, for a mass of 1287 kg, a carbonization duration of 4.14 h is calculated. This results in a throughput of 0.312 t h^{-1}. For energy demand, they report 553.65 kWh t^{-1}. The costs for the equipment are determined as for the precarbonization line and include, in addition to the rotary kiln, further auxiliary equipment. Including installation, etc., the costs for this process step per line amount to 2,290,000 EUR for Finland and 1,397,031 EUR for China.

For other plant parameters, such as sales, building, and general and administrative (G&A) costs, NG production of [24] is used as a reference. It is assumed that these cost components are identical for HC and NG production plants.

In the long term, however, we expect the focus to shift towards mass production of resin-derived hard carbon - such as from phenolic resins or plastic precursors - with coal- and asphalt-derived carbons serving as supplementary sources.

For the future 2030 hard carbon electrode modeled in this study, we assume phenolic resin as the precursor material. Although resin-based precursors are more expensive, they offer the advantage of synthetic control over structure, allowing for targeted property optimization, including improved rate performance. Even though these materials are still at an early stage of industrial adoption, we assume the same processing costs as for high-end materials in the baseline scenario.

- **High-end HC:** Coconut shells as the precursor, the yield throughout the manufacturing process is assumed to be ~81 % based on industry feedback (95 % for crushing, 90 % for purification, 95 % for carbonization) and the yield from coconuts is 25 % based on [35] which leads to an overall yield of ~20 %.

- **Mid-end HC:** Coconut shells as the precursor but the yield is slightly higher in the manufacturing process as less processing is performed. Furthermore, we still assume a pitch-coating, given the significant lower electrical conductivity of HC and the higher specific surface area (SSA) compared to AG or NG.

- **Low-end HC:** Pitch as the precursor and the yield of the manufacturing process is assumed like for the biomass-based HC. The initial yield from the pitch conversion is assumed to be 56 % as reported in [36]. We do not remove the coating step for the low-end HC, given the previously mentioned low electrical conductivity. Although the manufacturing process is more complex than conventional biomass-based routes, as untreated pitch tends to form graphitic structures during carbonization and therefore requires pretreatment to modify its microstructure [37], to simplify the analysis we assume that the processing cost are like biomass-based HC and consequently ~ 2.57 EUR kg^{-1}. Given the need to carefully control environmental impacts - particularly flue gas and wastewater emissions - the process costs for current pitch-based hard carbons may be even higher.
- **Future HC:** Phenolic resin is utilized as the precursor and the conversion yield is assumed as 40 % based on [36]. Due to the already high purity and low ash content of the precursor, no additional purification step is required in the process. The manufacturing yield is assumed to be like biomass-based HC and we also include a coating step. Like pitch-based HC, we did not model the process explicitly and assume that the processing cost are like for the biomass-based HC (except for the purification).

1.3.4 LFP

The model for LFP active material production is based on an own build PBCM derived from industrial data. The baseline process comprises raw material mixing, ball milling, spray drying, sintering, jet milling, and packaging as shown in Figure 8. The equipment parameters required for the PBCM are defined according to the requirements specified in Table 19.

Figure 8: Standard solid-state production process of LFP primarily based on industrial data

The production process varies depending on the material grade, which in this study is primarily classified based on compaction density. Accordingly, the process must be modelled in such a way that compaction density is optimized while being accurately reflected in the cost structure. In general, achieving a high compaction density for LFP requires a controlled combination of large and small particle fractions. At the same time, BEV requirements demand high fast-charging capability and long cycle life, which can be achieved through doping and surface coating of LFP particles. However, the incorporation of doping and coating materials inhibits particle growth during synthesis. Therefore, higher material grades for the solid-state process generally require a two-step calcination approach. In the first calcination step, LFP with a large particle size is synthesized. In the second calcination step, doping and coating agents, together with additional raw materials, are introduced to form a composite material consisting of both large- and small-particle LFP fractions. Due to confidentiality constraints further details on the adjustment in the process required for higher LFP material grades cannot be disclosed. However, a schematic overview of the process is shown in Figure 9.

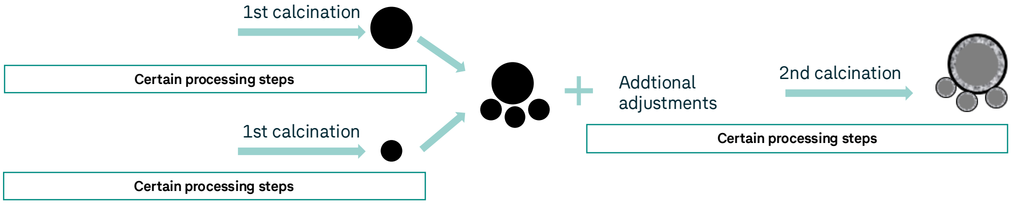

Figure 9: Schematic overview for producing higher material grades of LFP assuming two batch synthesis

For all material grades we model for the LFP plant operation behind the Heihe-Tengchong-Line for China and assume an operating time of 90 % (equal to 7689 h year^{-1}) and a factory size of 30 kt year^{-1}. We furthermore assume 3 working shifts per day and tailored overhead costs (logistics, indirect labor, machinery, etc.) for the LFP active material production plant.

Table 11: Modelled process cost for different LFP grades for China and Finland

Material grade	China [EUR kg^{-1}]	Finland [EUR kg^{-1}]
Low-end LFP	0.66	1.40
Mid-end LFP	0.91	1.73
High-end LFP	1.31	2.25

1.3.5 NFM and NCZNMT

For the active material production of the layered oxides NFM and NCZNMT, a solid-state process is modeled. Although co-precipitation is often reported for layered oxides, the all-solid-state ("precursor-free") route is considered more industrially stable for NFM. Accordingly, an NFM and NCZNMT production plant is modeled based on industrial data. The process steps consist of raw material mixing, a first calcination, crushing and sieving, another mixing step, a second calcination, crushing and sieving, iron removal and packaging. The equipment parameters required for the PBCM are, like for the LFP plant, defined according to the requirements specified in Table 19.

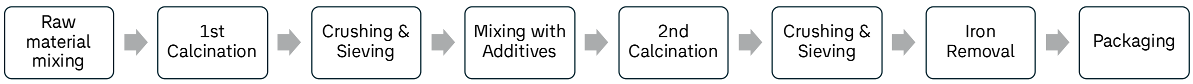

Figure 10: Solid-state or „precursor-free" production process of NFM and NCZNMT based on industrial data

We assume plant operation behind the Heihe-Tengchong-Line for China and in Europe in Hungary, an operating time of 90 % (equal to 7689 h year^{-1}) and a factory size of 30 kt year^{-1}, too. The other required parameters and the overhead costs (logistics, indirect labor, machinery, etc.) for the layered oxide active material production plant are the same as for the LFP production plant. The process cost shown in Table 12 include the expenses for labor, energy and equipment depreciation.

Table 12: Modelled process cost for NFM and NCZNMT for China and Hungary

Material	China [EUR kg^{-1}]	Hungary [EUR kg^{-1}]
NFM and NCZNMT	1.30	2.69

1.4 Electrolyte

1.4.1 $LiPF_6$-based

For LIBs, we assume an electrolyte formulation based on a blend of ethylene carbonate (EC) and ethyl methyl carbonate (EMC) with $LiPF_6$ as the conducting salt. For cost calculations, we use the 2024 average market prices reported by SMM for China. For Europe, we assume 30 % higher production costs for $LiPF_6$, analogous to the cost differential observed in active material production. In calculating total electrolyte costs, we assume a salt concentration of 1 mol L^{-1}, which reflects a standard formulation for LIB electrolytes.

Table 13: Price data for $LiPF_6$ for different scenarios

Scenario	China $LiPF_6$ [EUR kg^{-1}]	Europe $LiPF_6$ [EUR kg^{-1}]	Source
Baseline (2024)	7.10	9.20	SMM and for Europe extrapolated

Table 14: Price data for $LiPF_6$-based Electrolyte for different scenarios

Scenario	China Electrolyte [EUR kg^{-1}]	Europe Electrolyte [EUR kg^{-1}]	Source
Baseline (2024)	1.97	2.30	SMM and for Europe extrapolated

1.4.2 $NaPF_6$-NaFSI-based

For NIBs, we assume an electrolyte composed of a blend of propylene carbonate (PC), ethyl methyl carbonate (EMC), and diethyl carbonate (DEC), with $NaPF_6$ and NaFSI as the conducting salts. For $NaPF_6$ pricing, we adopt the cost reported by Yao et al. [23], following their rationale that current market prices may overstate the true cost of $NaPF_6$. Unlike $LiPF_6$, where lithium constitutes a significant portion of the cost, sodium is considerably less expensive, and its substitution should result in a lower cost conducting salt. For NaFSI we use price data from SMM from 2025, as data from 2024 is not available.

We assume a concentration of 1 mol L^{-1}, consistent with standard formulations. For European production, we apply a 30 % cost increase to reflect higher production costs analogous to the assumptions made for $LiPF_6$.

Table 15: Price data for $NaPF_6$ for different scenarios

Scenario	China $NaPF_6$ [EUR kg^{-1}]	Europe $NaPF_6$ [EUR kg^{-1}]	Source
Baseline (2024)	2.40	3.12	SMM and for Europe assumed

Table 16: Price data for NaFSI for different scenarios

Scenario	China NaFSI [EUR kg^{-1}]	Europe NaFSI [EUR kg^{-1}]	Source
Baseline (2024)	15.49	20.14	SMM 2025 data and for Europe assumed

Table 17: Price data for $NaPF_6$-based Electrolyte for different scenarios

Scenario	China Electrolyte [EUR kg^{-1}]	Europe Electrolyte [EUR kg^{-1}]	Source
Baseline (2024)	2.88	3.74	SMM and for Europe assumed

1.5 Battery cell production

For modelling the cost of battery cell production the equations of [38] are mainly used. A production scale of 20 GWh is assumed for both NIB and LIB technologies, representing a typical battery cell manufacturing plant size. Accordingly, factory layouts differ between the technologies, as larger equipment capacity and footprint are required to achieve 20 GWh of NIB cell production compared to LIB cells. Region-specific cost factors are applied to equipment to account for differences in investment cost structures between Europe and China, in addition to raw material cost differences. These factors are based on [39] and amount to 0.52 for China relative to 1.0 for Europe.

Table 18: Overview of general parameters for the battery cell production gigafactory

Parameter	Value	Unit	Source
Workdays per year	320.00	Days/year	Assumed
Number of shifts	3	Shifts/day	Assumed
Hours per shift	8	h/shift	Assumed
Overall equipment effectiveness	85.50	%	[38]
Useful life of machines	7.00	Years	[38]
Useful life of building	33.00	Years	[38]
Calculatory interest rate	6.00	%	[38]
Indirect labour costs	15.00	%	[38]
Logistics labour costs	15.00	%	[38]
Machine costs	1.00	%	[38]
Building costs	0.50	%	[38]
Logisitics costs	5.00	%	[38]
Indirect costs	0.50	%	[38]
Building energy consumption	101.80	$kWh\ m^{-2}\ year^{-1}$	[38]
Information system	MES system	-	-
Product certification requirements	CE	-	-
Coding and packaging requirements	Automatic coding	-	-

1.5.1 Process flow diagram

Figure 11 illustrates a simplified process flow sheet for the production of a prismatic cell and highlights the key differences between NIBs and LIBs, either in terms of processing parameters or equipment. While transitioning from one technology to another always requires adjustments across a wide range of process steps, only the most cost-relevant differences are emphasized here. Some of the necessary process modifications are beneficial for NIB production, whereas others adversely affect cost efficiency. Due to confidentiality constraints, detailed information regarding specific process differences cannot be disclosed. In addition to the process steps, the dry-room requirements for NIB manufacturing differ from those of LFP-based LIBs. Specifically, NIBs demand stricter environmental control, comparable to that required for high-Ni NCM systems.

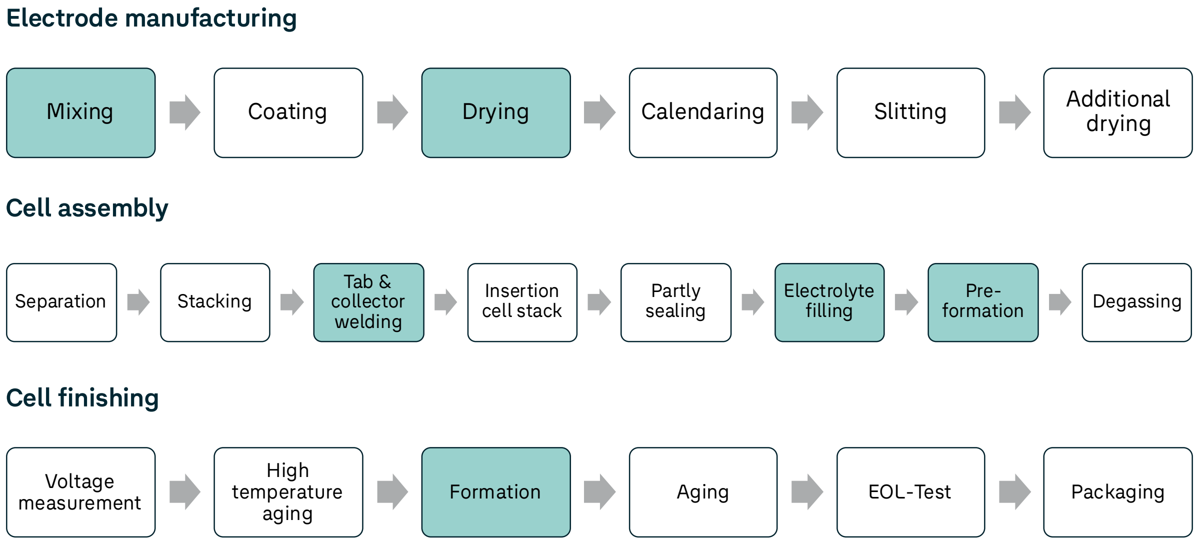

Figure 11: Production steps for NIB and LIB battery cells and the respective differences (highlighted in green) affecting the costs between the two technologies

1.5.2 Equipment parameters

The relevant equipment parameters of the machines for the respective process steps are presented in Table 19. Due to confidentiality reasons, detailed equipment data at the process level cannot be disclosed. The parameters summarized include the installation and capital expenditure costs of the respective tools, the scrap rate as well as production tolerances, the number of required operators, performance data, and additional utility requirements such as nitrogen, compressed air, and water. In addition, the footprint of each machine is considered. These parameters are then used to design the battery cell production facility and input for each process step in the PBCM.

Table 19: Required equipment parameters

Parameter	Unit
Equipment installation cost	EUR
Tooling investment	EUR
Scrap rate	%
Production tolerance	%
Direct operators	FTE
Indirect operators/staff (logistics, quality, etc.)	FTE
Rated power (peak)	kW
Utilized power (normal operation)	kW
Nitrogen consumption	m^3/h
Compressed air consumption	m^3/h
Water consumption	m^3/h
Area Footprint (only machinery)	m^2
Other	-

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