A Techno-Economic Model for Benchmarking the Production Cost of Lithium-Ion Battery Cells

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Table S1 includes the unit price of material components as well as the unit price of the relevant machinery for each process step in the battery cell manufacturing plant.

Table S1. Unit price of material components and the relevant machinery

Set index	Set content	Parameter	Value	Unit	Reference
H	$\mathcal{p}^{h}_{CAM}$	Lithium Carbonate process factor	5.32	[$/kg]	[1]
		Nickel Sulfate process factor	2.64	[$/kg]	[1]
		Manganese Sulfate process factor	2.75	[$/kg]	[1]
		Cobalt Sulfate process factor	2.63	[$/kg]	[1]
G	$\overline{P}^{g}_{CAM}$	Average price of lithium	30.12	[$/kg]	[2]
		Average price of nickel	19.79	[$/kg]	[2]
		Average price of manganese	1.22	[$/kg]	[2]
		Average price of cobalt	59.50	[$/kg]	[2]
		Average price of aluminum	2.67	[$/kg]	[2]
I	P^{i}_{mat}	Cathode active material	Based on Equations 1 and 2	[$/kg]	Equations 1 and 2
		Conductive black carbon	5.89	[$/kg]	[3]
		Binder cathode	7.08 [1]	[$/kg]	[4]
		Binder anode	10.0	[$/kg]	[5]
		Solvent cathode (NMP)	3.10	[$/kg]	[6]
		Anode active material graphite	11.0	[$/kg]	[7]
		Anode active material LTO	9.0	[$/kg]	[8]
		Anode active material Si-NW	66.0	[$/kg]	[9]
		Electrolyte	15	[$/liter]	[1]
J	P^{j}_{mat}	Separator	1.0	[$/m^2]	[10]
		Positive current collector foil	0.1 [2]	[$/m^2]	[11]
		Negative current collector foil	0.99 [3]	[$/m^2]	[12]
K	P^{k}_{mat}	Cell container	0.25	[$/item]	[6]
		Positive terminal	0.28	[$/item]	[6]
		Negative terminal	0.41	[$/item]	[6]
U [4]	$\widetilde{P}^{u=mix,cat}$	Cathode Mixer	7.28 - 13.76	[M$/base case size]	[13]
	$\widetilde{P}^{u=mix,and}$	Anode Mixer	6.21 - 11.72	[M$/ base case size]	[13]
	$\widetilde{P}^{u=drr}$	Dry room	20.00 - 22.00	[M$/base case]	[14]
	$\widetilde{P}^{u}_{mch}$	Coating and drying cathode	6.24 - 13.64	[M$/Production line]	[13]
		Coating and drying anode	5.76 - 12.60	[M$/Production line]	[13]
		Calendering cathode	1.87 - 3.75	[M$/Production line]	[13]
		Calendering anode	1.87 - 3.75	[M$/Production line]	[13]
		Slitting cathode	1.12 - 6.00	[M$/Production line]	[13]
		Slitting anode	1.12 - 6.00	[M$/Production line]	[13]

Vacuum drying	4.50 – 8.99	[M$/Production line]	[13]
Winding	11.24 – 26.24	[M$/Production line]	[13]
Packaging (contacting + inserting + sealing)	7.49 – 14.50	[M$/Production line]	[13]
Filling (Filling + final Sealing)	9.00 - 13.55	[M$/Production line]	[13]
Formation cycling	52.48 - 67.43	[M$/Production line]	[13]
Aging	3.73 – 7.45	[M$/Production line]	[13]
Testing	3.73 – 6.00	[M$/Production line]	[13]

[1] Converted from Euro to US$ [15], [2] Converted from (US$/ton) to (US$/m^2) based on the thickness of positive current collector in the battery cell, [3] Converted from (US$/ton) to (US$/m^2) based on the thickness of negative current collector in the battery cell, [4] Converted from Euro to US$ [15] and adjusted to the required size of model based on Equation S1.

Regarding the unit price of production lines for each process step in Table S1, in the battery process model [16], a capacity of around 2 GWh per year is presupposed as a base case study where the plant is working at its full capacity, meaning the sizing of all production lines has been based upon this assumption. This assumption is also regarded as the basis of unit price for machines in the plant. Ranges of prices for the state-of-the-art machinery and equipment for the base case study are extracted from [13]. The considered prices in Table S1 have been adjusted to the base case capacity of [16] using the classical six-tenths rule [17],

$$P_{mch,des} = P_{mch,ava} \times \left(\frac{\theta_{des}}{\theta_{ava}}\right)^{P_{mch}} \tag{S1}$$

where $P_{mch,des}$ is the desired equipment cost, $P_{mch,ava}$ is the available equipment cost, θ_{des} is the production volume for the target case study, and θ_{ava} is the production volume for the available machinery cost. In addition, P_{mch} indicates the relevant scaling power factor for machinery, assumed to be 0.6 in this work.

Table S2. Fractional distribution of the operators between different process steps in the battery cell manufacturing plant

Unit in the process chain	Percent allocation of operators to units in a working shift [%] [1]
Cathode Mixer	-
Anode Mixer	-
Cathode coating and drying	12.5%
Anode coating and drying	12.5%
Cathode calendering	5%
Anode calendering	5%
Cathode slitting	3.75%
Anode slitting	3.75%
Vacuum drying	Included in drying unit
Winding	12.5%
Packaging [2]	12.5%
Filling [3]	12.5%
Formation cycling	12.5%
Aging	3.75%
Testing	3.75%
Dry room	-

[1] Labor for the mixing and the dry room is explained in Section 2.2.4, [2] Packaging includes contacting of terminals, insertion into the house, and welding the battery house, [3] After the filling, cells are sealed. This step is included in the filling step.

Regarding the input parameters for both process and cost models, the relevant parameters of the NMC111-G battery cell, the case study battery cell, for the process model are listed in the first section of Table S3.

In addition, the common parameters of the cost model for all the locations in this study are listed in the second section of Table S3, and Table S4 includes the parameters which vary with the location of the plant including labor, energy, land and construction, and interest rate.

Table S3. Relevant parameters of the battery cell in the case study as inputs to the process and cost models

	Parameter	Value	Unit	Reference
Process model	E_{spf}	264	(Wh/kg)	[16]
	w	70	(mm)	
	l	235	(mm)	
	N_{bcl}	37	-	
	R	5%	-	[14]
	S	8%	-	[16]
Cost model	λ_{lab}	74%	-	[18–20]
	λ_{nrg}	14%	-	[18–20]
	λ_{bld}	12%	-	[18–20]
	β	2.36	-	[1]
	τ_{mch}	6	(year)	[14]
	N_{shf}	3	(day^{-1})	[16]
	τ_{shf}	8	(hour/day)	[16]
	τ_{ubt}	40	(min/shift)	[21]
	τ_{nos}	0	(hour/day)	[22]
	N_{wpy}	300	(days/year)	[16]
	τ_{bld}	20	(year)	[14]
	γ_{mnt}	10%	-	[14]
	γ_{ovh}	33%	-	[14]
	α_{tch}	11%	-	[23]
	$\alpha_{ind,lab}$	46%	-	[23]
	$\alpha_{mch,ins}$	0.06 - 0.12	-	[24]

Regarding the unit price of electricity, the values used in the project at hand are calculated based on the electricity bill for 1,000,000 (kWh) annual industrial consumption, including the cost of power, distribution, and taxes.

Considering the wage for labor, three different costs for each country are assumed in Table S4; the top one is considered for operators, the middle one is for technicians, and the low one is for indirect labor in the plant. Since the indirect labor comprises different classes of workers, an average hourly wage of five types is assumed, including service activities, professional and scientific, administrative and support service activities, electricity (gas, steam, and air conditioning supply), and water supply (sewerage, waste management, and remediation activities), to meet all requirements of the plant.

For European countries, data are collected from [25]. For China, operator wage is extracted from [26], and for technicians and indirect labor, [27] is used. Since the data are for 2019, they are adjusted using a ratio of 3.6% [28], which is an average rise in wage in China from 2019. For South Korea, the operator's salary is extracted from [29], and technicians' are extracted from [30]. Regarding the Japanese labor cost, data are extracted from the Japan Ministry of Health, Labour, and Welfare [31]. All of these assumptions are included in Table S4.

Table S4. Assumed economic factors to study the effect of location on the total cost of cell

Economic Factor	Location								
	US	Germany	Norway	Sweden	China [2]	Korea [3]	Poland	France	Japan [4]
Energy [1] ($/kWh) [32]	0.109	0.236	0.078	0.042	0.099	0.091	0.140	0.142	0.167
Land and Construction ($/m²) [33,34]	4072	4502	6161	5320	2184	3147	2307	4916	4801
Labor ($/hour) [24–31,35]	22.4 26.95 26.70	47.52 52.66 44.73	50.69 67.35 54.12	46.91 55.66 44.62	3.25 5.6 5.5	15.6 22 18.73	11.28 15.87 12.98	45.23 56.88 53.36	14.73 17.53 16.2
Interest rate [36,37]	2.3%	4.34%	6.69%	1.89%	3.65%	1.53%	7.64%	5.11%	1.07%

[1] Industrial unit price of energy has been assumed, [2] exchange rate 6.37 for CNY to US$ [15], [3] exchange rate 1196.5 for KRW to US$ [15], [4] exchange rate 0.0073 for JPY to US$

Table S5 includes all the data for different layers of the cost model for the case study battery cell chemistry in Section 3.1.

Table S5. A location-wise distribution of the total cell cost of the case study between defined layers of the cost model

Relevant parameter to layer	Description	US	Sweden	Poland	Germany	France	Norway	Korea	China	Japan
C_{msp}	Material	68.3	72.9	65.7	74.1	73.8	74.1	66.5	64.8	67.5
	Scrap	8.8	9.4	8.4	9.6	9.4	9.5	8.5	8.2	8.7
C_{nrg}	Energy	3.2	1.4	4.1	6.9	4.2	2.3	2.7	2.7	5.0
C_{lab}	Labor	12.1	25.3	6.0	25.6	24.4	27.3	8.4	1.7	7.9
C_{bld}	Land and buildings	3.5	4.4	3.0	4.6	5.3	7.5	2.5	2.1	3.7
C_{eqp}	Machinery and Installation	18.3	19.2	20.1	20.3	20.5	21.5	17.6	17.9	17.3
C_{mnt}	Maintenance	1.8	1.9	2.0	2.1	2.0	2.2	1.7	1.8	1.7
C_{ovh}	Overhead	7.7	8.4	8.2	8.8	9.2	10.2	7.2	7.2	7.5
C_{Cell}	Total battery cell	123.7	142.9	117.5	152.0	148.8	153.6	115.1	106.4	119.4

Table S6. Battery cell cost reported in works of literature and available cost models

Reference	Cell type	Production Volume [GWh.year $^{-1}$]	Year of study	Value [$/kWh]	Description	Number on Figure 5
[38]	NMC622-G	-	2010	390	- For production greater than 100000 packs per year	1
[39]	NMC111-G	-	2010	195	- Material level [3]	2
[5]	NMC	-	2014	310	-	3
[40]	NMC111-G	-	2015	502	- Battery pack level [1] - Baseline scenario is considered	4
[22]	NMC111-G	-	2015	230	- Battery pack level [1]	5
[41]	NMC111-G	-	2015	188	- Battery pack level [1]	6

					- Annual production of 235000 battery packs	
[39]	NMC111-G	-	2015	170	- Material level [3]	7
[14]	NMC111-G	2	2017	243	- Baseline scenario	8
[14]	NMC111-G	2	2017	180	- Optimistic scenario	9
[42]	NMC622-G	-	2017	432	- Battery pack level [1] - Low production quantities	10
[43]	NMC111-G	-	2018	59	- Electrode stack level [2]	11
[38]	NMC111-G	-	2018	150	- For production greater than 100000 packs per year	12
[1]	NMC111-G	5	2019	177.45	- Battery pack level [1] - Calculated with interpolation between 2 GWh and 8 GWh for 66% material cost share	13
[6]	NMC111-G	5.3	2020	116	- Based on energy use of cell	14
[38]	NMC622-G	-	2020	130	- For production greater than 100000 packs per year	15
[44]	NMC811-G	6	2020	119	-	16
[45]	NMC111-G	-	2020	169	- Battery pack level [1]	17
[46]	-	-	2020	102	-	18
[47]	NMC622-G	35	2021	106	- Base scenario is considered	19
[48]	-	-	2021	131	Considering annual decrease ratio of 0.13 based on their work to adjust 2020 data to 2021	20
[49]	-	-	2021	101	-	21
[50]	-	-	2021	157	- Battery pack level [1] - Production of 100000 packs per year	22
[47]	NMC-G	35	2021	64	- Optimized scenario	23
US (BCS)	NMC111-G	5.3	2021	123.7	- Case study of current work	US (BCS)
US (MES)[4]	NMC111-G	7.8	2021	108.3	- Minimum efficient scale of current work	US (MES)
[38]	NMC622-G	-	2025	115	- For production greater than 100000 packs per year	24
[51]	-	-	2025	78	- Total cell cost includes profit - 24M technology	25

[1, 2, 3] Reported costs in the battery pack, material, and electrode stack levels need to be converted to the battery cell level, [4] the total battery cell cost calculated based on the minimum efficient scale of the plant, discussed in Section 3.3 of this work.

As mentioned in the footer of Table S6, some data in literature and cost models have been reported in battery pack level, material, or electrode stack level. To make an accurate comparison, these data are required to be adjusted to cell cost level by the application of some coefficients extracted from literature and industry. König et al. [52] has been excerpted for relevant ratios based on [1,34,43,53,54] to develop cell cost to battery pack level for three different years. According to the reported value for 2020 in their work, the cell-to-pack cost ratio ranges from 1.94 to 2.21, with a mean value of 2.07. Duffner et al. [47] applied 1.31 as a corrective factor to convert material level to cell cost level and 0.75 for a battery pack to the cell level. Voelcker et al. [55] applied 48% as a scaling factor from cell level to pack. Mauler et al. [56] conducted a detailed study on recent peer-viewed publications, [38,46,57,58], to acquire relevant ratios for converting each level of cost analysis to cell level. These ratios are found in Table S7.

Table S7. Relevant ratios to convert different levels of cost to cell level [56]

Level of cost	Ratio
Cell to battery pack	30.89%
Electrode stack level to material	16.14%
Material level to cell	33.51%

Implementing the ratios from Table S7 updates Table S6 to the cell cost level. The updated data are presented in Figure 5 to compare the case study of the current project with recent cost models.

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