Delivering the 3b generation of LNMO cells for the xEV market of 2025 and beyond

Large-scale manufacturing for 3beLiEVe cells

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Project Abstract

3beLiEVe aims to strengthen the position of the European battery and automotive industry in the future xEV market by delivering the next generation of battery cells, designed and made in Europe, for the electrified vehicles market of 2025 and beyond. The project activities are focused on three domains:

- Development of automotive battery cells that are highly performant (high energy density, fast charge capability, long cycle life) and free of critical raw materials such as cobalt and natural graphite;
- Development and integration of sensors into and onto the cells to enable smart, adaptive operating strategies and advanced diagnostics to extend the useful life of the battery in first and second-life applications and improve safety;
- A comprehensive manufacturing approach that is designed from the outset for a circular economy and industrial volumes. This encompasses green manufacturing processes for cell, module and pack, as well as recyclability assessment of the components, and a target lifecycle cost of 90 €/kWh at scale.

The project will deliver two 12kWh-demonstrator battery packs at TRL6 and MRL8. These aim at demonstrating the 3beLiEVe technology performance for applications in light duty (i.e. passenger cars, freight vehicles) and commercial vehicles (i.e. city buses and trucks) in fully electric/plug-in hybrid (BEV/PHEV) configurations.

The strong and complementary consortium of 21 partners from 10 different European countries representing industrial companies, SMEs, RTOs and academia is coordinated by AIT Austrian Institute of Technology. 3beLiEVe is scheduled to run from January 1st, 2020 to June 30th, 2023, for a total duration of 42 months and has received funding from the European Union's H2020 research and innovation programme under Grant Agreement no. 875033. A full list of partners and funding can be found at: https://cordis.europa.eu/project/id/875033.

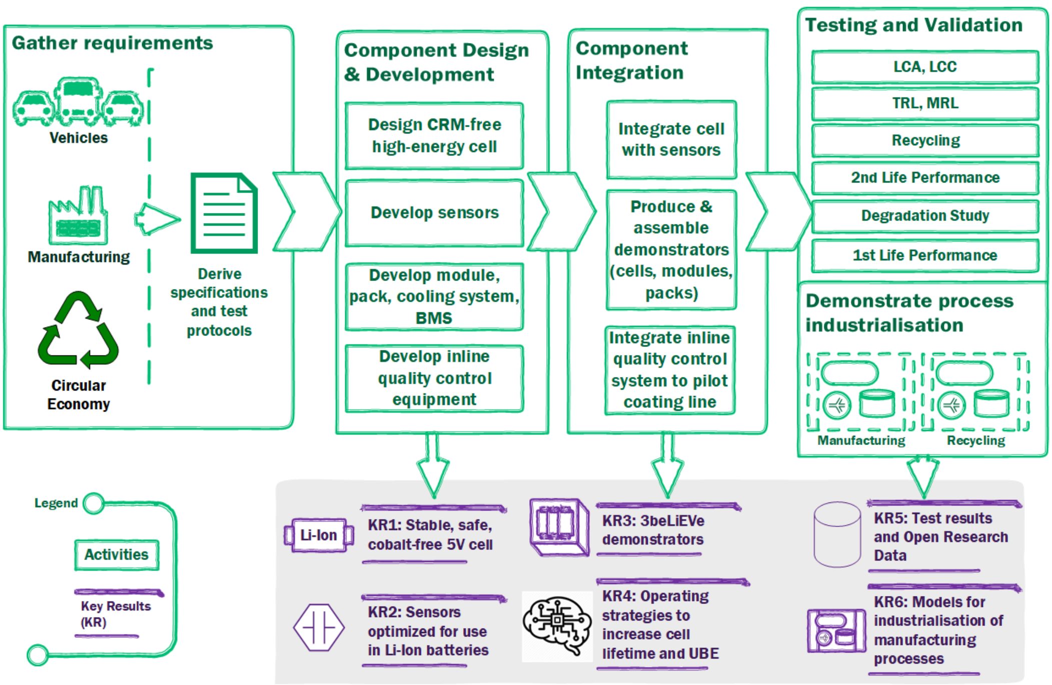

Figure 1: Overview of major 3beLiEVe project steps

Executive Summary

To understand the requirements for and implications of GWh-scale production of the developed battery technology, 3beLiEVe encompasses the design and simulation of LMNO cell production at the Gigafactory level as an integral part of its research activities. In the first phase, the manufacturing processes and methods for electrode production, cell assembly, and finishing have been simulated using the Siemens Tecnomatix Plant Simulation 15 software, virtualizing a 1 GWh/year baseline production plant of the 3beLiEVe cell relying upon the portfolio of MANZ machinery. The base production line including all units required for 3beLiEVe battery production has been defined, providing very detailed and visual insights regarding the material flows and energy consumption. The objective of the second phase was the scale-up of the virtual model to the targeted cell manufacturing capacity of a 10 GWh/year Gigafactory plant. This was achieved by analyzing the potential for scalability of equipment and processes, selecting the most suitable solutions, and finally organizing the plant in modules that can grant efficiencies of scale and flexibility in the plant operation.

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List of abbreviations

Acronym / Short Name	Meaning
AGV	Automated guided vehicle
DI WATER	De-Ionized Water
FEN	Fast Electrode Notching Machine, used to cut the electrode shape starting from a coil
H.T.	Higher than room temperature; used to accelerate physical processes like drying, soaking, or aging
HBW	High bay warehouse, an automated multiple floor warehouse
Hi-Pot	High potential, an electrical test aimed at verifying the insulation of cell layers
Li-Ion	Lithium ion
LNMO	Lithium Nickel Manganese Oxide
MTBF	Mean time between failures
MTTR	Mean time to repair
OEE	Overall Equipment Effectiveness
R.T.	Room temperature
WMS	Warehouse management system

1. Introduction

The manufacturing pillar of the 3beLiEVe project addresses the ambition of upscaling 3beLiEVe battery chemistry at a gigawatt-hour scale, and it encompasses the following topics:

- Demonstrating the manufacturing methods for cells, modules, and packs in a virtual environment
- Developing and implementing new equipment for inline quality inspection at the pilot line level
- 3beLiEVe cells, modules, and packs after first life: 2nd life applications, disassembly, and recycling.

To understand the requirements for and implications of GWh-scale production of the developed technology, 3beLiEVe encompasses the design and simulation of LMNO cells at the Gigafactory level as an integral part of its research activities. Here, the manufacturing processes and methods for electrode production, cell assembly, and finishing have been simulated using the Siemens Tecnomatix Plant Simulation software, virtualizing 1 GWh/year and 10 GWh/year Gigafactory based on 3beLiEVe cell chemistry via an appropriate process chain model. The assumptions on cell design and equipment that were used for the simulations are detailed in Section 2. In the first phase, a single production line with a 1 GWh/year output was devised that includes all units required for 3beLiEVe battery production. Once the single production line has been defined and validated, the potential for scaling up equipment and processes was analyzed. Based on the results of the analysis, the structure of a cell manufacturing plant with a targeted capacity of 10 GWh/year was defined. The models for the 1 and 10 GWh/year plants include essential machine parameters controlling the process flow by considering the intermediate product parameters at each step. The production lines were assumed to be operative 300 days/year in three shifts for a total of 6300h per year. The model enables the definition of logical material flows inside each unit based on 3beLiEVe cell requirements and calculates in real-time the energy consumption of existing units in the battery production lines by incorporating randomly distributed machine failures. The model allows for understanding the complex interactions between different units in a Gigafactory environment, managing the resources, increasing the machine throughputs, optimizing the layout of the factory, and improving the material flow while eliminating jams and reducing scraps.

The virtualization activity covers the processes required to produce 3beLiEVe batteries at a cell level. For the main processes, Figure 2 summarizes the major steps involved in electrode production, cell assembly, and cell finishing, respectively. Each process was modelled in two dimensions (2D) in Siemens Tecnomatix environment. This document is structured as follows: Section 2 describes the main assumptions used in the model, Section 3 gives a detailed description of each process simulated in the 1 GWh/year plant, including also an example of 3D modelling applied to specific processes, namely electrode notching and cell finishing; Section 0 presents the organization of the 10 GWh/year plant, the expected flows of materials and energy consumption, highlighting the optimizations obtained with the scale-up from 1 GWh/year.

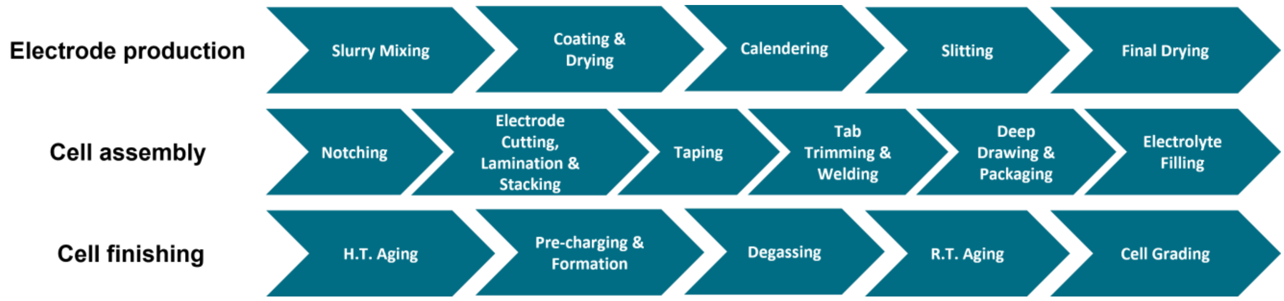

Figure 2: Overview of major 3beLiEVe cell manufacturing processes.

2. Model assumptions

This section shows the main assumptions that were used for developing the models. Data regarding electrode manufacturing process and cell design is reported in section 2.1; the technical specifications of the machines used in the model are presented in section 2.2.

2.1. Electrode and cell design

The composition and density of the slurries and of the dried coatings are reported in Table 1.

ANODE		CATHODE	
Dry electrode composition		**Dry electrode composition**	
	wt %		wt %
Graphite	76.50	LMNO	89.73
Silicon	13.50	Carbon black	4.99
Carbon black	1.91	Binder 1 (LBG)	1.99
Binder 1 (CMC)	1.91	Additive (2150)	0.30
Binder 2 (SBR)	1.91	Binder 2 (PVDF)	2.99
Electrode properties		**Electrode properties**	
Porosity %	33.00	Porosity %	45.80
Calendered density (g/cm^3)	1.46	Calendered density (g/cm^3)	2.04
Gravimetric capacity (mAh/g)	392.26	Gravimetric capacity (mAh/g)	121.10
Volumetric capacity (mAh/cm^3)	573.55	Volumetric capacity (mAh/cm^3)	246.48
Slurry composition		**Slurry composition**	
Solids	wt %	*Solids*	wt %
Graphite	30.60	LMNO	61.91
Silicon	5.40	Carbon black	3.44
Carbon black	0.77	Binder 1 (LBG)	1.38
Binder 1 (CMC)	0.77	Additive (2150)	0.21
Binder 2 (SBR)	0.77	Binder 2 (PVDF)	2.06
Solvents	wt %	*Solvents*	wt %
DI Water (slurry)	35.89	Acetone	12.43
DI Water (CMC)	23.17	NMP (slurry)	0.00
DI Water (SBR)	0.94	NMP (PVDF)	18.57
Slurry properties		**Slurry properties**	
Slurry density (g/cm^3)	1.28	Slurry density (g/cm^3)	1.91
Solids % in slurry	40.00	Solids % in slurry	69.00

Table 1 Technical specifications of electrode coating and slurry.

The geometrical sizes of anode and cathode are reported in Table 2. The main cell parameters are summarized in Table 3.

	Sheet Width	**Sheet Length**	**Thickness**
	[mm]	**[mm]**	**[mm]**
Anode Coating (Active Material, Per Side)	320	95	0.05
Anode Bare foil	27.5	95	0.01
Cathode (Active Material, Per Side)	318	93	0.1055
Cathode Bare foil	27.5	93	0.015

Table 2 Geometrical size of electrodes.

Double sided cathodes	**46**	
Double sided anodes	46	
Voltage	4.4	V
Capacity	70	Ah
Energy	308	Wh
Cell thickness	17.60	mm

Table 3 Cell parameters.

2.2. Machine specifications

The technical specifications of the machines used in the 1 and 10 GWh/y were obtained from Manz technical department, partners, and publicly available sources. When data was not directly available, the values were estimated.

2.2.1. Slurry mixing

Batch mixing line (1 GWh/year)

The batch mixing line was used for the 1 GWh/year plant and consists of three mixers that alternately supply slurry to the coating line. We assumed that slurry preparation, including degassing, requires 6 hours, while washing and drying the mixer before preparing a new batch takes 1 hour. The operating cycle is shown in Table 4. The technical specifications of the batch mixing line are shown in Table 5.

Duty cycle (3 mixers)	hours 1-6	hours 7-12	hours 13-18
mixer 1	supplying slurry	washing, drying and waiting	preparing slurry
mixer 2	preparing slurry	supplying slurry	washing, drying and waiting
mixer 3	washing, drying and waiting	preparing slurry	supplying slurry

Table 4 Operating cycle of the batch mixing plant.

Mixer max capacity	**1750**	**L**
Mixer max load	3500	kg
Operators per shift	2	
Energy consumption	224	kWh/t
Number of mixers per line	3	
Dimensions		
Length	14	m
Width	9	m
Height	8	m
Availability	99.0%	
Performance	99.0%	
Quality	99.5%	
OEE	97.5%	

Table 5 Technical specifications of the batch mixing line.

Continuous mixing line (10 GWh/year)

The continuous mixing line was used for the 10 GWh/year plant and is based on a twin screw extruder with a diameter of 125 mm that can produce up to 2500 kg/h of slurry, coupled to three buffer tanks. The technical specifications are reported in Table 6. Continuous mixing is reportedly more energy efficient compared to batch mixing, with an estimated energy consumption of 56 Wh/kg of slurry.

Output max	**2500**	kg/h
	1923	L/h
Operators per shift	1	
Energy consumption	56	kWh/t
Dimensions		
Length	19	m
Width	9	m
Height	15	m
Availability	99.0%	
Performance	99.0%	
Quality	99.8%	
OEE	97.8%	

Table 6 Technical specifications of the continuous mixing line.

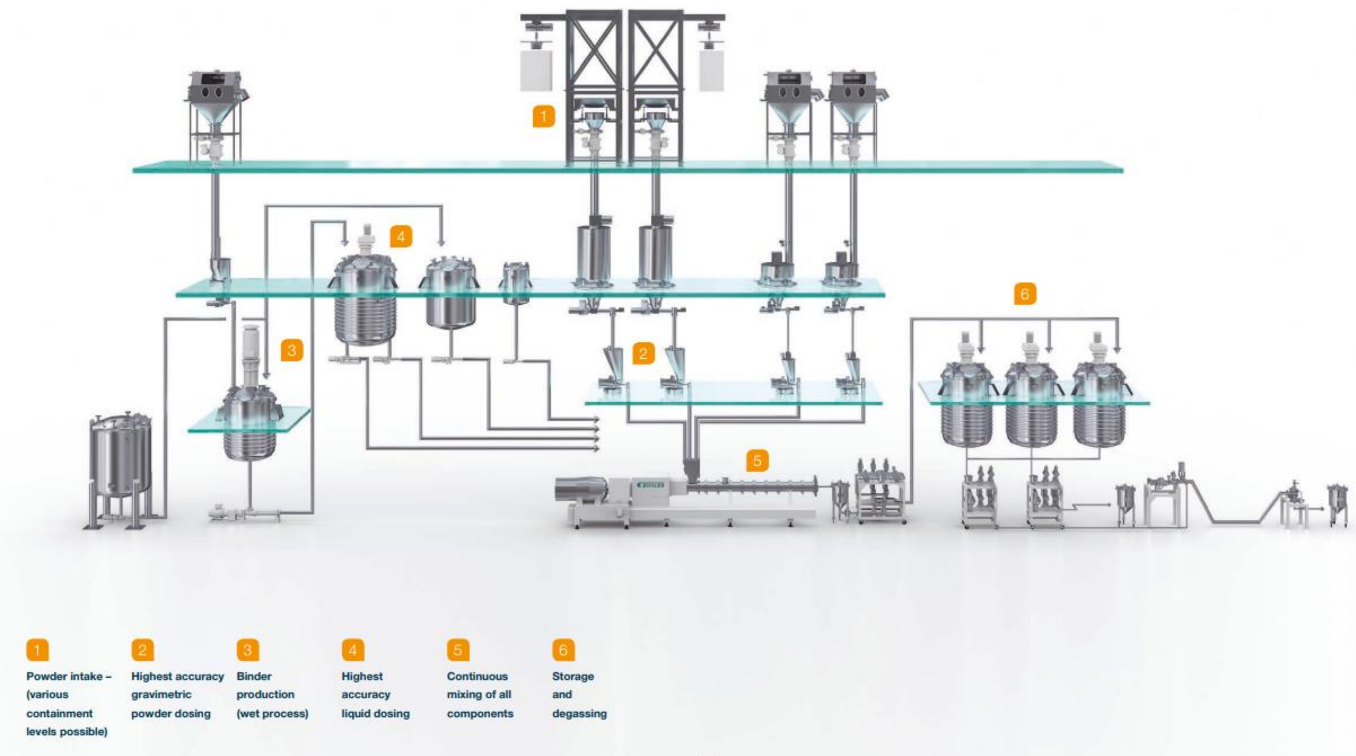

Figure 3- Continuous Mixing plant [Buhlergroup.com Efficient Continuous Electrode Slurry Production]

2.2.2. Coating and drying

Coating and drying machines are slot die coating units followed by a linear oven dryer with a solvent recovery and purification system that can recover >99% of solvent. The two sides of the electrode are coated and dried simultaneously. The machine technical specifications for the 1 GWh/year and 10 GWh/year coating and drying equipment are reported in Table 7. We assumed that drying anodes and cathodes requires a permanence time in the oven of 1.2 and 2 minutes respectively, considering the different coating thicknesses and solvents used.

Speed	**20-80**	**m/s**
Operators per shift	1	
NMP recovery	>99%	
Reusable NMP	>95%	
Availability	99.0%	
Performance	99.0%	
Quality	99.8%	
OEE	97.8%	
Process parameters		
Sides coated simultaneously	2	
Drying time in oven (anode)	1.2	min
Drying time in oven (cathode)	2	min
1 GWh/y		
Electrode Width		
anode	695	mm
cathode	691	mm
Oven length		
anode	27	m
cathode	43	m
Power		
anode and cathode	1500	kW
10 GWh/y		
Electrode Width		
anode	1390	mm
cathode	1382	mm
Oven length		
anode	67	m
cathode	72	m
Power		
anode and cathode	3000	kW

Table 7 Technical specifications of drying and coating lines.

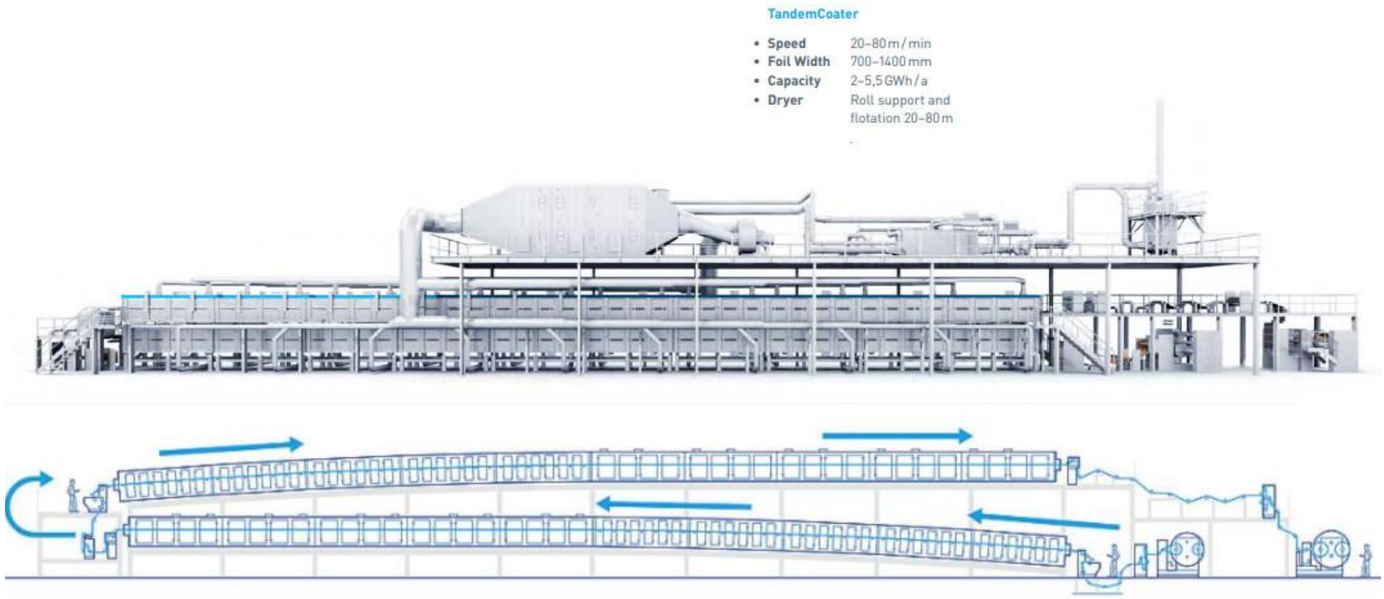

Figure 4 Tandem Coating Line Durr.com

2.2.3. Calendering

The specification of the calendering machines are reported in Table 8. The estimated machine footprint is 12 m by 7 m.

Max speed		
1 GWh/y	50	m/min
10 GWh/y	140	m/min
Power		
1 GWh/y	45	kW
10 GWh/y	270	kW
Operators per shift	1	
Dimensions		
Length	12	m
Width	7	m
Height	3	m
Availability	99.0%	
Performance	99.0%	
Quality	99.5%	
OEE	97.5%	

Table 8 Technical specifications of calendering machines.

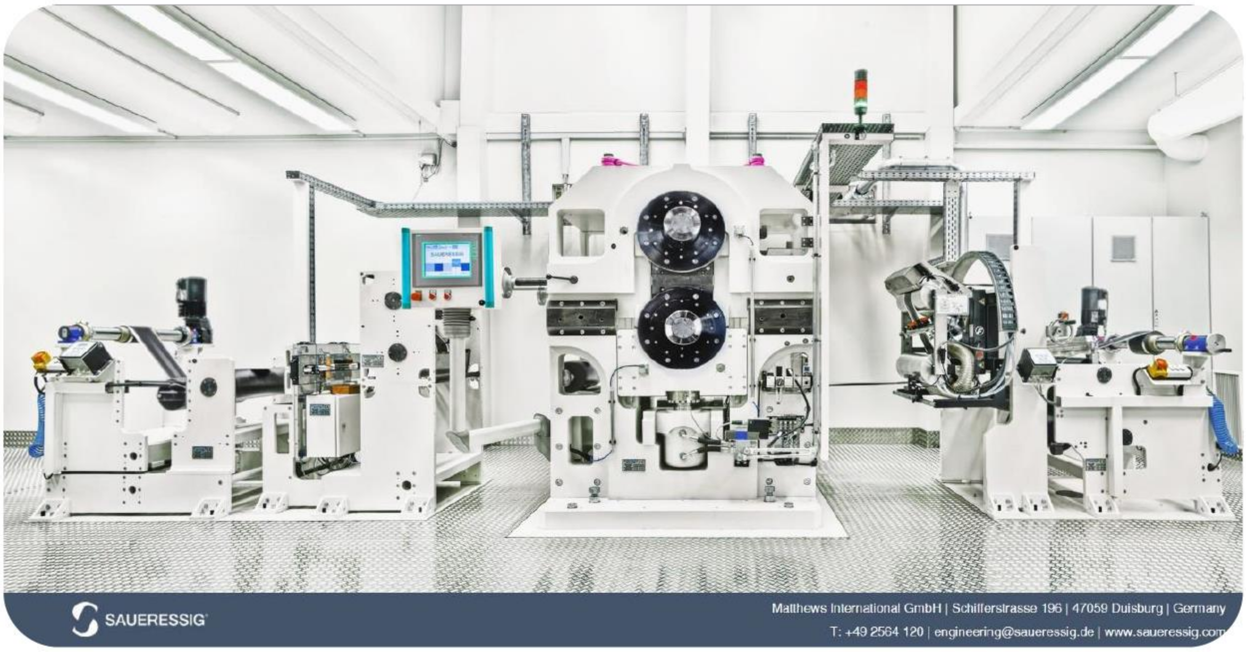

Figure 5 Calendering Machine Saueressig.com

2.2.4. Slitting

The specification of the slitting machines are reported in Table 9.

Max Speed	**140**	m/min
Operators per shift	1	
Dimensions per machine		
Length	10	m
Width	4.5	m
Height	3	m
Power		
1 GWh/y	22	kW
10 GWh/y	44	kW
Availability	99.0%	
Performance	99.0%	
Quality	99.5%	
OEE	97.5%	

Table 9 Technical specifications of slitting machines used in the 1 GWh/year plant.

Figure 6 Automatic Roll Change Electrode Slitting Machine , LEAD INTELLIGENT EQUIPMENT GMBH Leadgp.com

2.2.5. Notching

Notching machines cut part of the electrode web to expose tabs and that will form the electrical connections to the electrodes in the cell. The technical specifications of the notching machines were taken from Manz Fast Electrode Noching machine (FEN), which has a maximum electrode speed of 1000 mm/s and maximum notching rate of 360 strokes per minute. For the simulations we hypothesized the use of a triple notching tool that can cut three tabs in a single stroke. The technical specifications are shown in Table 10.

Max strokes per minute	**360**	spm
Notching tool size	3	cells
Max tabs/min	1080	ppm
Max web speed	1000	mm/s
Operators per shift	1	
Dimensions per machine		
Length	7.7	m
Width	2.1	m
Height	2.2	m
Peak power	40	kW
Average power	2.6	kW
Availability	96.0%	
Performance	99.0%	
Quality	99.0%	
OEE	94.1%	

Table 10 Technical specifications of the notching machine.

Figure 7 Electrode Notching Machine, MANZ AG Manz.com

2.2.6. Cell lamination and stacking

Lamination and stacking machines laminate pairs of anode and cathode with two layers of separator to form monocells, which are stacked to form what will be the active part of the pouch cell. The technical specifications of the lamination and stacking machine were taken from Manz MLS 209 machine. The technical specifications are shown in Table 11.

Max monocells/min	**300**	ppm
Max web speed	800	mm/s
Electrode reel outer diameter max	700	mm
Electrode reel weight max	300	kg
Separator reel weight max	60	kg
Belt protector weight max	60	kg
Dimensions per machine		
Length	12.5	m
Width	2.1	m
Height	2.3	m
Operators per shift	2	
Peak power	105	kW
Power consumption (production)	42	kW
Availability	91.0%	
Performance	99.0%	
Quality	98.0%	
OEE	88.3%	

Table 11 Technical specifications of the Lamination and Stacking machine.

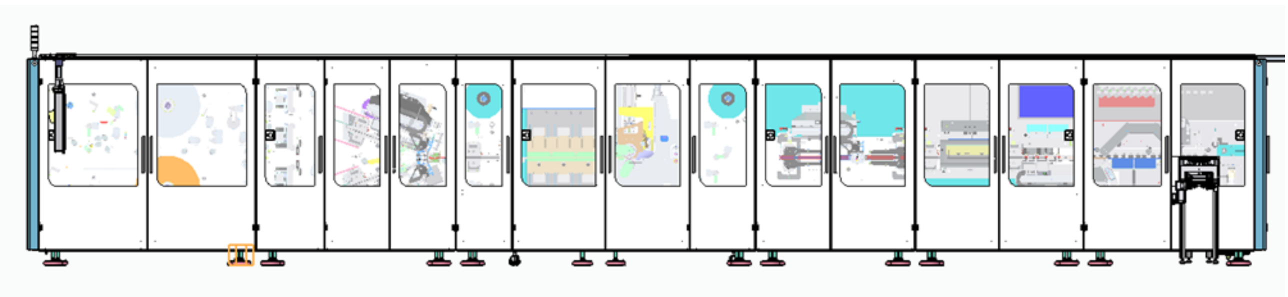

Figure 8 Cell Lamination and Stacking, MANZ AG Manz.com

2.2.7. Cell taping

Taping machines apply six adhesive tape strips on the stack of monocells to keep them aligned. The machine modelled for the 3beLiEVe gigafactories has a maximum throughput of 16 ppm and an average electrical load of 6 kW. The technical specifications are shown in Table 12.

Max stack per minute	**16**	ppm
Operators per shift	1	
Peak power	10	kW
Average power	6	kW
Availability	98.0%	
Performance	99.0%	
Quality	99.0%	
OEE	96.0%	

Table 12 Technical specifications of the taping machine.

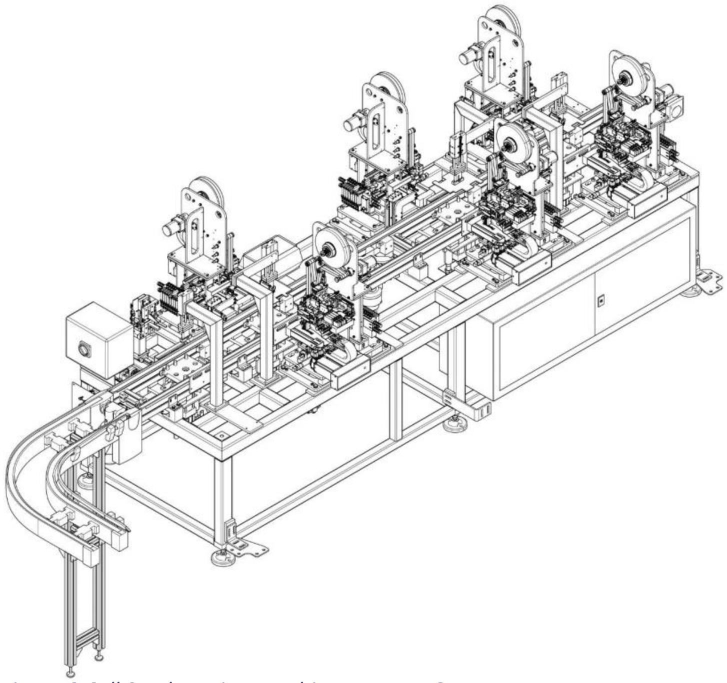

Figure 9 Cell Stack Taping Machine, MANZ AG Manz.com

2.2.8. Tab trimming and welding

The tab trimming and welding (TTW) machine welds together the tabs of the monocells in the stack to connect them in parallel, trims the excess material, then welds the cell's anode and cathode to current collectors, i.e. metal sheets exposing anode and cathode connections to the exterior. The specifications are shown in Table 13.

Max stack per minute	**16**	ppm
Operators per shift	1	
Peak power	60	kW
Average power	30	kW
Availability	94.0%	
Performance	99.0%	
Quality	98.0%	
OEE	91.2%	

Table 13 Technical specifications of the tab trimming and welding machine.

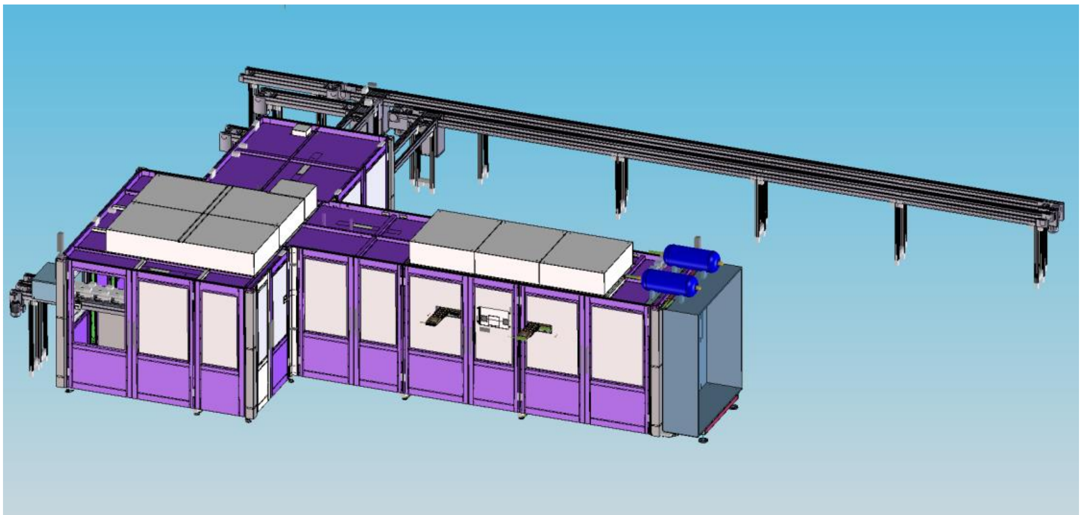

Figure 10 Tab Trimming and Welding, MANZ AG Manz.com

2.2.9. Deep drawing and packaging

The deep drawing and packaging (DDP) machine prepares the pouch bag packaging and inserts the cell stack. The specifications are shown in Table 14.

Max stack per minute	**16**	ppm
Operators per shift	1	
Peak power	80	kW
Average power	40	kW
Availability	96.0%	
Performance	97.0%	
Quality	98.0%	
OEE	91.3%	

Table 14 Technical specifications of the deep drawing and packaging machine.

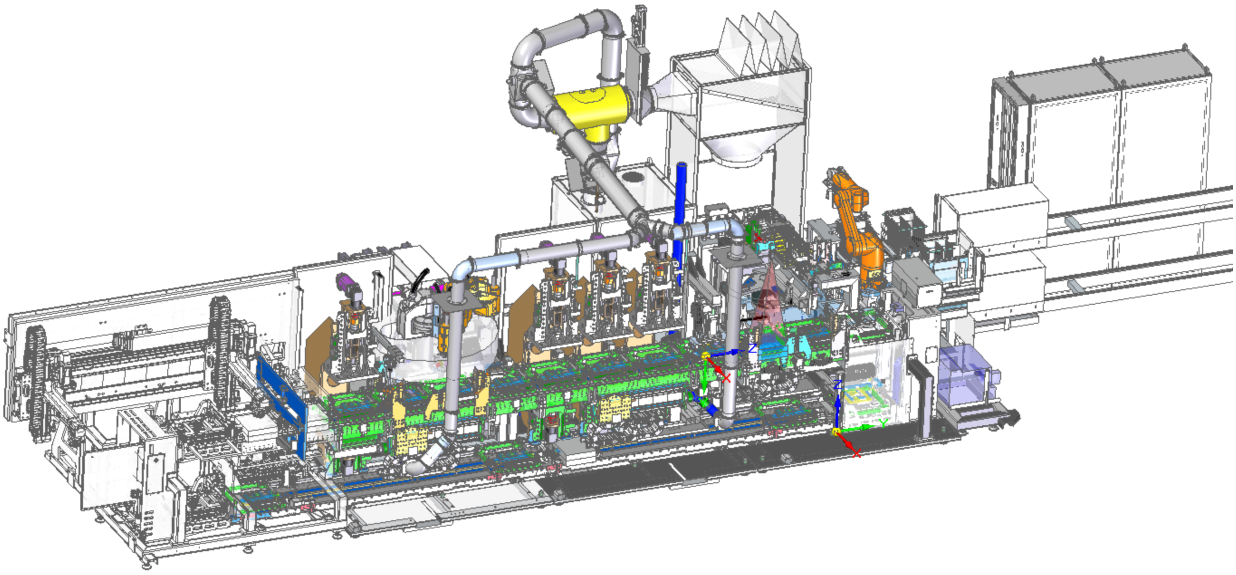

Figure 11 Pouch Cell Packaging Machine, MANZ AG Manz.com

2.2.10. Filling

The electrolyte filling machine has a maximum output of 16 cells per minute. Technical specifications are shown in Table 15.

Max cells per minute	**16**	ppm
Operators per shift	1	
Peak power	50	kW
Average power	30	kW
Availability	97.0%	
Performance	98.0%	
Quality	98.0%	
OEE	93.2%	

Table 15 Technical specifications of the filling machine.

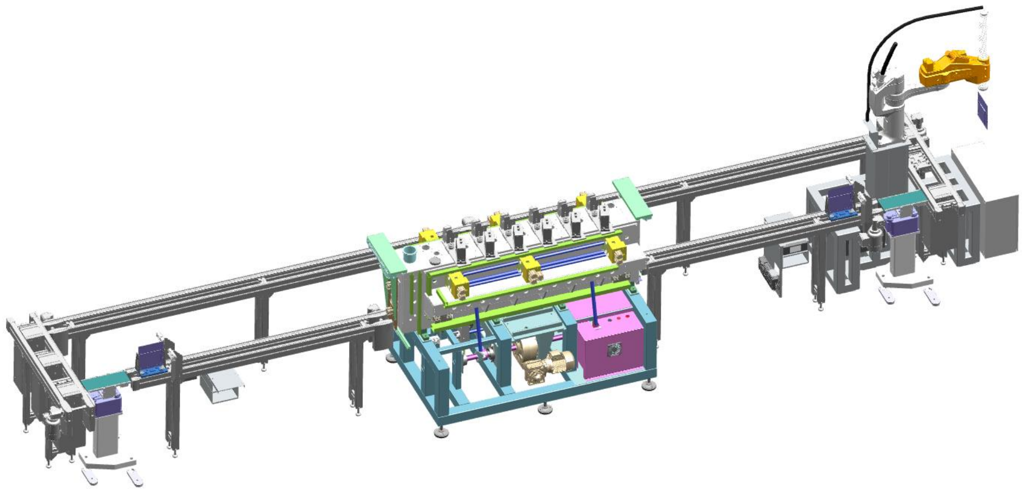

Figure 12 Cell Filling Line , Manz AG Manz.com

2.2.11. Cell finishing

The cell finishing area comprise several machines and warehouses where long aging and cycling processes take place. To ease the management of warehouses, cells are loaded in trays containing 32 cells. To estimate the warehouses' dimensions, we assumed a height of 12 m and a volume occupancy of 0.5 m^3 per tray. The first process, high temperature aging, is needed to ensure a good wetting of the cell by the electrolyte; parameters used in the modelling are shown in Table 16.

Duration	12	h
Temperature	45	°C
Tray capacity	32	
Warehouse height	12	m
Volume occupied by tray in warehouse	0.512	m^3
Operators per shift	1	
Energy consumption	1	kW/m^2
Availability	99.9%	
Performance	99.9%	
Quality	100.0%	
OEE	99.8%	

Table 16 Parameters defining the high temperature aging step.

During formation the cell is charged and discharged multiple times at low rate to form a stable interface between the active materials and the electrolyte; partially recovering energy during the discharge phase. The assumptions of the model are shown in Table 17.

Pre-charge time	4	h
Formation time	15	h
Total process time	19	h
Tray capacity	32	
Warehouse height	12	m
Volume occupied by tray in warehouse	0.512	m^3
Operators per shift	1	
Energy consumption	10	Wh/Wh cell
Availability	99.9%	
Performance	99.9%	
Quality	99.0%	
OEE	98.8%	

Table 17 Parameters defining the pre-charging and formation step.

Degassing and sealing is carried out in an automatic machine which removes the gas developed during the initial formation cycles and permanently seals the pouch cell; technical specifications are shown in Table 18.

Max stack per minute	**16**	ppm
Operators per shift	1	
Peak power	50	kW
Average power	30	kW
Availability	98.0%	
Performance	98.0%	
Quality	99.0%	
OEE	95.1%	

Table 18 Parameters defining the cell degassing machine.

After degassing, the cells undergo a further 1 week aging phase in a warehouse at room temperature; the parameters used for the simulation are shown in Table 19.

Duration	**168**	h
Temperature	22	°C
Tray capacity	32	
Warehouse height	12	m
Volume occupied by tray in warehouse	0.512	m^3
Operators per shift	1	
Energy consumption	0.2	kW/m^2
Availability	99.9%	
Performance	99.9%	
Quality	100.0%	
OEE	99.8%	

Table 19 Parameters defining the room temperature aging step.

Finally, the cells are graded by few charge and discharge cycles and sorted based on their actual capacity; this phase was simulated using assumptions shown in Table 20.

Cycling time	**2**	h
Tray capacity	32	
Warehouse height	12	m
Volume occupied by tray in warehouse	0.512	m^3
Operators per shift	1	
Energy consumption	1	Wh/Wh cell
Availability	99.9%	
Performance	99.9%	
Quality	98.0%	
OEE	97.8%	

Table 20 Parameters defining the cell grading and sorting process.

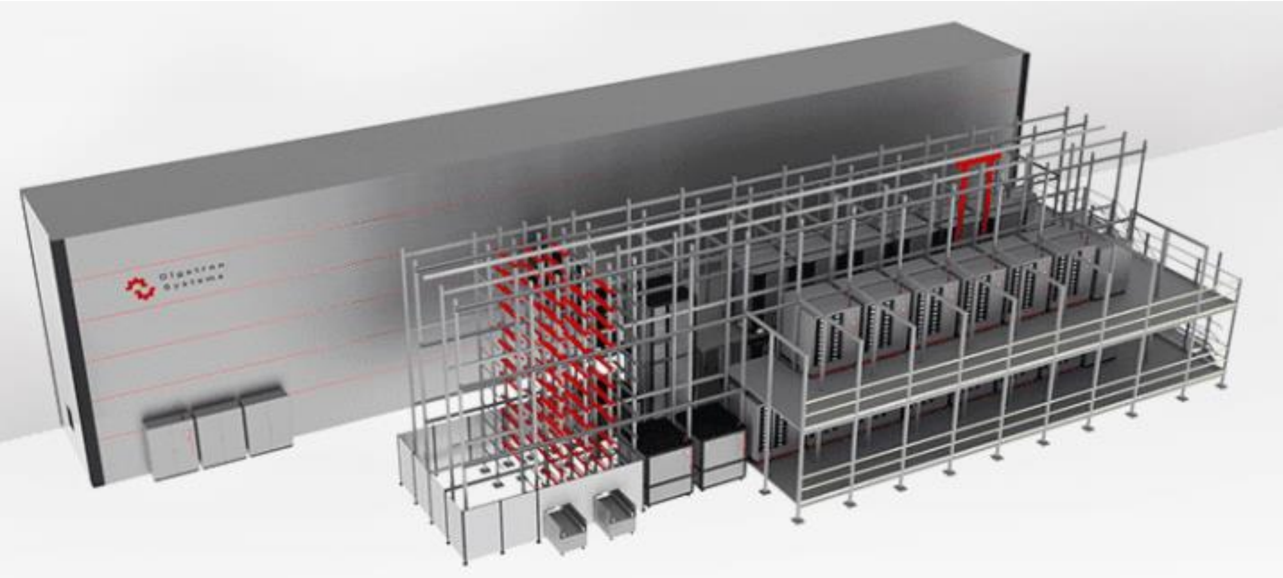

Figure 13 Cell Formation and ageing automated plant , DigatronSystems.com

3. Simulation of cell manufacturing processes for a 1 GWh/year plant

The full process chain of the cell production was modelled in 2D. The model incorporates the organizational data including working hours, shift system as well as process and machine parameters like cycle time and energy demand. Area planning including occupied machine footprints, inter-machine distances, buffering areas, etc. was also considered. Where necessary, conveyor systems, workers, and automated guided vehicles (AGV) were introduced to guarantee efficient material flow within the production. The total number of machines installed and operators working per shift are shown in Table 21. Overall, the 1 GWh/year plant produces 3.25 million good quality cells per year (515 cells per hour) and occupies a surface of about 10,000 m^2; due to losses occurring in all manufacturing steps, only 85.4% of the materials handled go into usable batteries (Table 22). The energy consumed by the plant is estimated to be about 50 GWh/year, with detailed contributions from the production phases shown in Table 23.

	Machines	**Operators**
Anode mixing	1	2
Anode coating & drying	1	1
Anode Calendering	1	1
Anode slitting	1	1
Anode final drying	1	1
Total Anode manufacturing	**5**	**6**
Cathode mixing	1	2
Cathode coating & drying	1	1
Cathode Calendering	1	1
Cathode slitting	1	1
Cathode final drying	2	1
Total Cathode manufacturing	**6**	**6**
Total electrode manufacturing	**11**	**12**
Anode notching	1	1
Cathode notching	1	1
Lamination and stacking	2	4
Taping	1	1
Tab trimming and welding	1	1
Deep drawing & packaging	1	1
Electrolyte filling	1	1
Total cell assembly	**8**	**10**
High temperature aging	1	1
Pre-Charging & Formation	1	1
Degassing	1	1
Room temperature aging	1	1
Grading & Sorting	1	1
Total cell finishing	**5**	**5**
TOTAL MANUFACTURING PLANT	**24**	**27**

Table 21 Number of machines installed in the 1 GWh/year plant and number of operators working per shift.

Anode manufacturing quality	**97.3%**
Cathode manufacturing quality	97.3%
Cell assembly quality	91.3%
Cell finishing quality	96.0%
Overall cell production quality	**85.4%**

Table 22 Quality of products at different stages of the 1 GWh/year plant.

Electrode Manufacturing	**21.4**	GWh/y
Cell assembly	1.2	GWh/y
dry room	1.0	GWh/y
conveyor belts	0.05	GWh/y
Cell finishing	11.8	GWh/y
Coil handling	0.06	GWh/y
Building consumption (200 W/m2)	14.4	GWh/y
Total energy consumption from cell manufacturing	**49.9**	GWh/y
Energy consumption per unit of product	**49.9**	Wh/Wh of product

Table 23 Energy consumption of the 1 GWh/year plant.

3.1. Electrode Production

The mixing process was modeled as shown in Figure 14; due to its lower initial cost, a batch mixing line was chosen for the 1 GWh/year scale. The equipment encompasses the sources of the active material, binder, conducting carbon as well as solvent that are connected to the mixer with a dosing system. The method takes the material properties, doses a certain amount of each material at a defined sequence by the electrode recipe to the mixer and controls the mixing time and the mixing speed. After mixing, and before transferring the slurry to the coating machine, the slurry passes through a buffering system to ensure continuous feeding of the following processes.

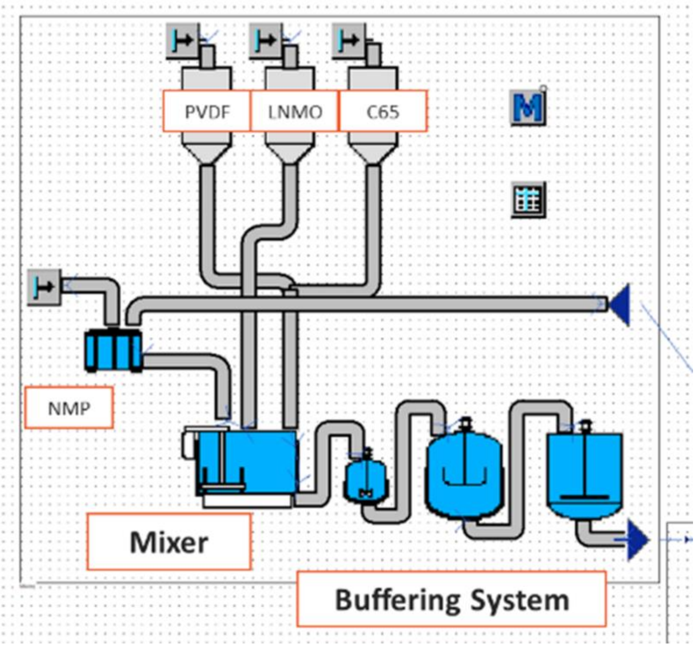

Figure 14: 2D simulation of LNMO cathode slurry mixing.

Subsequently, the cathode and anode slurries are coated on aluminium and copper current collectors, respectively (Figure 15). In the 2D simulation of the coating and drying process, the slot-die coating was modelled with a portioner at a defined coating rate per area of the current collector. The coated electrode passes through four chambers at different temperatures, undergoing the drying temperature profiles. The evaporated solvent is then passed through a solvent recovery system. Dried electrodes are rewound and transferred to the calendering machine.

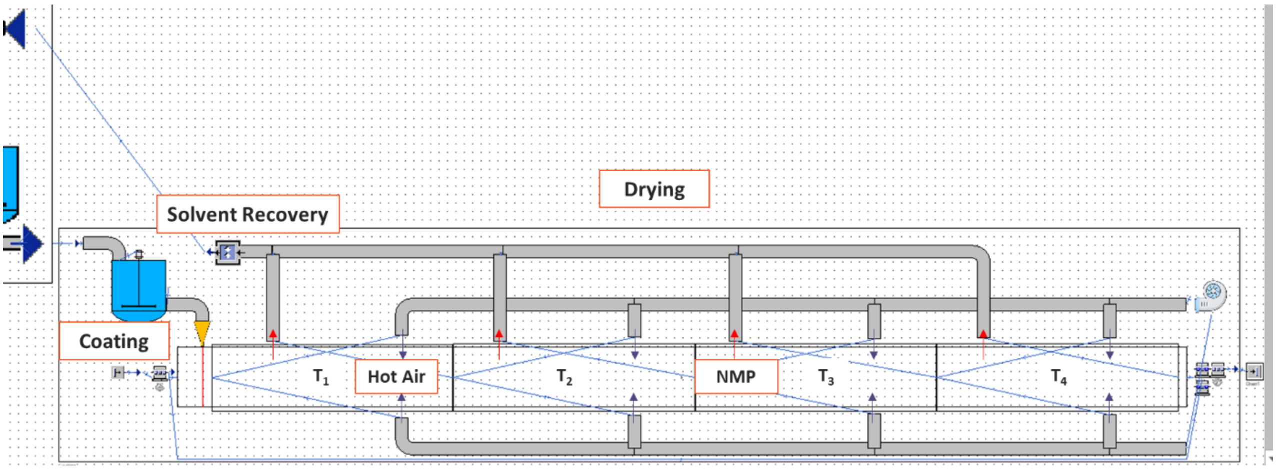

Figure 15: 2D simulation of coating and drying process

Dried-coated electrodes are then calendered to reach desired compactness in the calendering machine through a roll-to-roll process (Figure 16 (left)). For each machine, the energy demand was calculated based on the average energy of the machines at different states. Assuming continuous operation, the calculated energy represents the average value between the energy consumption of the machine at states of setting up, working, and standby. Afterwards, calendared coils of electrodes are slit in the slitting machine. Two daughter coils are extracted from each jumbo coil as shown in Figure 16 (right).

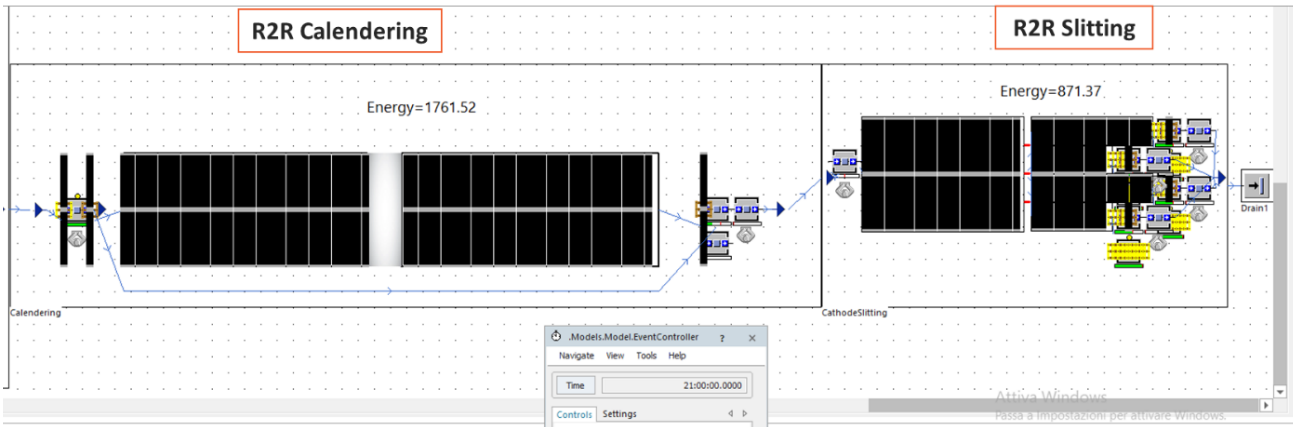

Figure 16: 2D simulation of calendaring (left) and slitting processes (right).

Finally, the slit coils are dried in vacuum dryers at temperatures from 80 °C to 120 °C before being transferred to the dry room.

3.1.1. Material flows and energy consumption.

The average material flow and slurry production rates necessary to achieve a final cell production volume of 1 GWh/year are reported in Table 24. Part of the slurry (0.5%) is wasted while washing the mixers before preparing a new batch.

Anode		Cathode	
Machines	1	Machines	1
Quantities per machine			
Solids in kg/h	125.26	**Solids in kg/h**	357.91
Graphite kg/h	95.83	LMNO kg/h	321.15
Silicon kg/h	16.91	Carbon black kg/h	17.84
Carbon black kg/h	2.40	Binder 1 (LBG) kg/h	7.14
Binder 1 (CMC) kg/h	2.40	Additive (2150) kg/h	1.07
Binder 2 (SBR) kg/**h**	2.40	Binder 2 (PVDF) kg/h	10.71
Solvents in	187.90	**Solvents in kg/h**	160.80
DI Water slurry kg/h	112.41	NMP slurry kg/h	0.00
DI Water CMC kg/h	72.56	NMP (PVDF) kg/h	96.35
DI Water SBR kg/h	2.93	NMP Total kg/h	96.35
DI Water total kg/h	187.90	Acetone kg/h	64.45
Total in kg/h	313.16	**Total in kg/h**	518.71
Slurry out kg/h	311.60	**Slurry out kg/h**	516.11
Slurry out L/h	244.07	**Slurry out L/**h	270.13

Table 24 Material flow rates for the slurry mixing calculated for 1 GWh/year cell production.

The average power load of all mixing equipment is 186 kW, resulting in an energy consumption of 1.17 GWh/year.

The coating machines receive slurry from the mixers and spread it on both sides on a metal foil that is unwound from coils with a width of about 700 mm (695 mm, 691 mm for anode and cathode respectively). During drying, the solvent evaporates from the coating and is recovered. The material flow rates in the coating and drying process are reported in Table 25; the anode and cathode lines run at 22.2 m/min and 22.7 m/min respectively. Part of the slurry and the metal foil (0.2%) is wasted during starts and stops of production.

Anode		Cathode	
Machines	1	**Machines**	1
Quantities per machine			
Slurry in kg/h	311.60	**Slurry in kg/h**	516.11
Copper foil in m/h	1331.90	**Aluminum foil in m/h**	1303.86
Copper foil in m/min	22.20	**Aluminium foil in m/min**	21.73
Copper foil in kg/h	82.94	**Aluminium foil in kg/h**	36.49
Solvent out kg/h	186.58	**Solvent out kg/h**	159.68
Copper foil waste kg/h	0.17	**Aluminum foil waste kg/h**	0.07
Slurry waste kg/h	0.62	**Slurry waste kg/h**	1.03
Average Power kW	1500	**Average Power kW**	1500

Table 25 Material flow rates at the coating and drying machine of the 1 GWh/year plant.

Coating and drying are estimated to require an overall average power load of 3000 kW, resulting in an energy consumption of 18.9 GWh/year.

The dried electrodes are then calendered by machines that run at an average speed of 22.15 and 21.69 m/min for the anode and cathode lines respectively (Table 26), with a total average load of 90 kW and a yearly energy consumption of 0.57 GWh.

Anode		Cathode	
Machines	1	**Machines**	1
Quantities per machine			
Electrode in m/h	1329.24	**Electrode in m/h**	1301.25
Electrode in m/min	22.15	**Electrode in m/min**	21.69
Electrode in kg/h	207.16	**Electrode in kg/h**	391.82
Electrode waste kg/h	1.04	**Electrode waste kg/h**	1.96
Average Power kW	45	**Average Power kW**	45

Table 26 Material flow rates for the calendering machine.

The slitting machines cut the jumbo electrode reel into two daughter reels and run at average speeds of 22.15 m/min and 21.69 m/min for anode and cathode respectively (Table 27). Average power required is 90 kW in total, determining an energy consumption of 0.28 GWh/year.

Anode		Cathode	
Machines	1	**Machines**	1
Quantities per machine			
Electrode in m/h	1322.59	**Electrode in m/h**	1294.75
Electrode in m/min	22.04	**Electrode in m/min**	21.58
Electrode in kg/h	206.13	**Electrode in kg/h**	389.86
Electrode waste kg/h	1.03	**Electrode waste**	1.95
Average Power kW	22	**Average Power kW**	22

Table 27 Material flow rates for the slitting machine.

3.2. Cell assembly

The cell assembly processes take place inside a dry room atmosphere with a dew point of -50°C. Technical input data were derived from Manz automated machines.

Figure 17 depicts the schematic layout of the notching, lamination and stacking units. In the notching machine (Figure 17-left), dried coils are transferred to the dry room where all cell assembly processes take place. The material flow starts on the left with the unnotched coils of the cathode and the anode. The upper left and the lower left units correspond to the cathode notching and anode notching units, respectively. The notched electrodes are stored inside a buffer with a certain capacity. Then, the notched electrodes are fed to the unwinding reels of the lamination and stacking unit (Figure 17-right). The source of the separator coils provides the separator required in the lamination unit. In the lamination unit, the electrodes are cut and placed on the separators and passed through two sensors and stacked vertically. At the end of the lamination and stacking unit, those cells that successfully passed the geometrical check and electrical test are stacked.

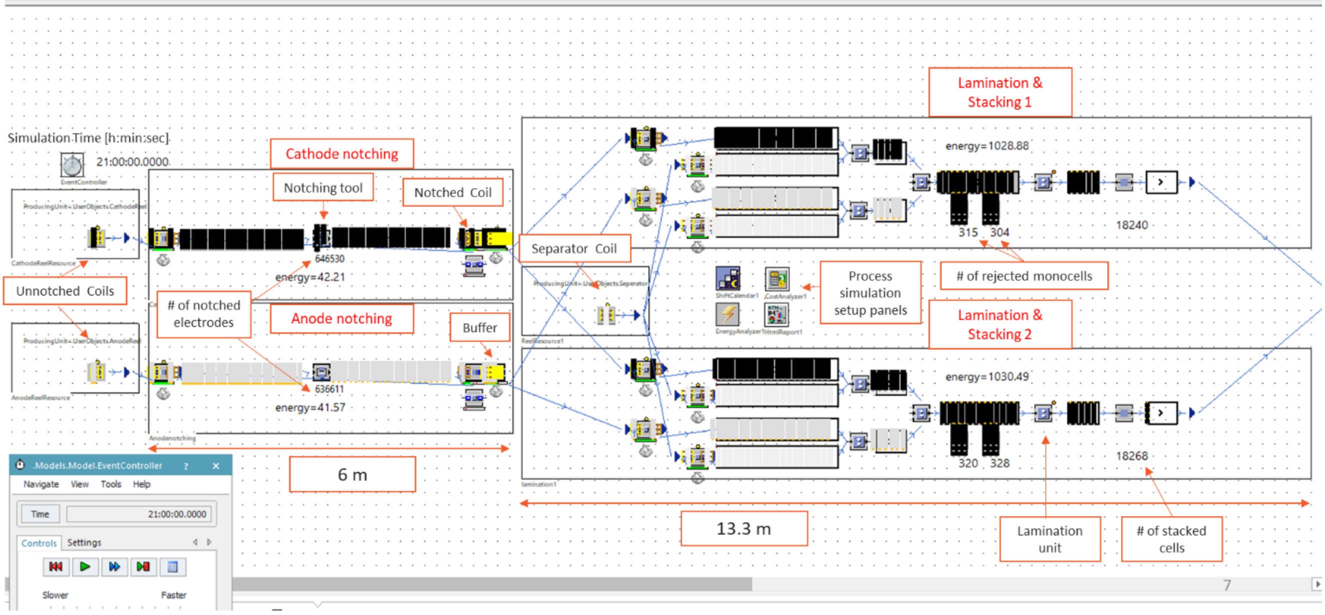

Figure 17: 2D simulation of notching (left) and lamination and stacking machines (right).

There are several characteristic parameters that must be monitored in each unit. For instance, the model keeps track of the number of notched electrodes produced in the notching unit, and the number of rejected mono-cells as well as those OK stacked cells at the end of the lamination and stacking unit. It is essential to calculate the occupied area by each unit and the interunit distance so that we can estimate the total area of the dry room required for the cell assembly. The model calculates in real-time the energy consumption of each unit to address the dynamic energy demand of the battery production. In this regard, the first attempt was to integrate the shares of machine power consumption in different operating states. The states of working, setting up, operational, failed, standby, and off were defined, and corresponding values of power demand were assigned to each state. The continuous processes in the cell assembly are characterized by long processing times and steady power demand. Therefore, an average power consumption value was estimated for each unit to reduce the cost of calculation.

The stack of mono-cells is fixed in a taping unit (Figure 18). Tab welding, deep drawing, and packaging, as well as electrolyte filling are the following units in the 3beLiEVe cell assembly line. The stacked and taped cells are introduced to the tab welding unit using a pick and place robot. The cells are clamped, and the tabs are welded to the cells, followed by a tab taping station. After a final Hi-Pot verification test, the failed cells are rejected to a container and the OK ones are transferred to the packaging unit.

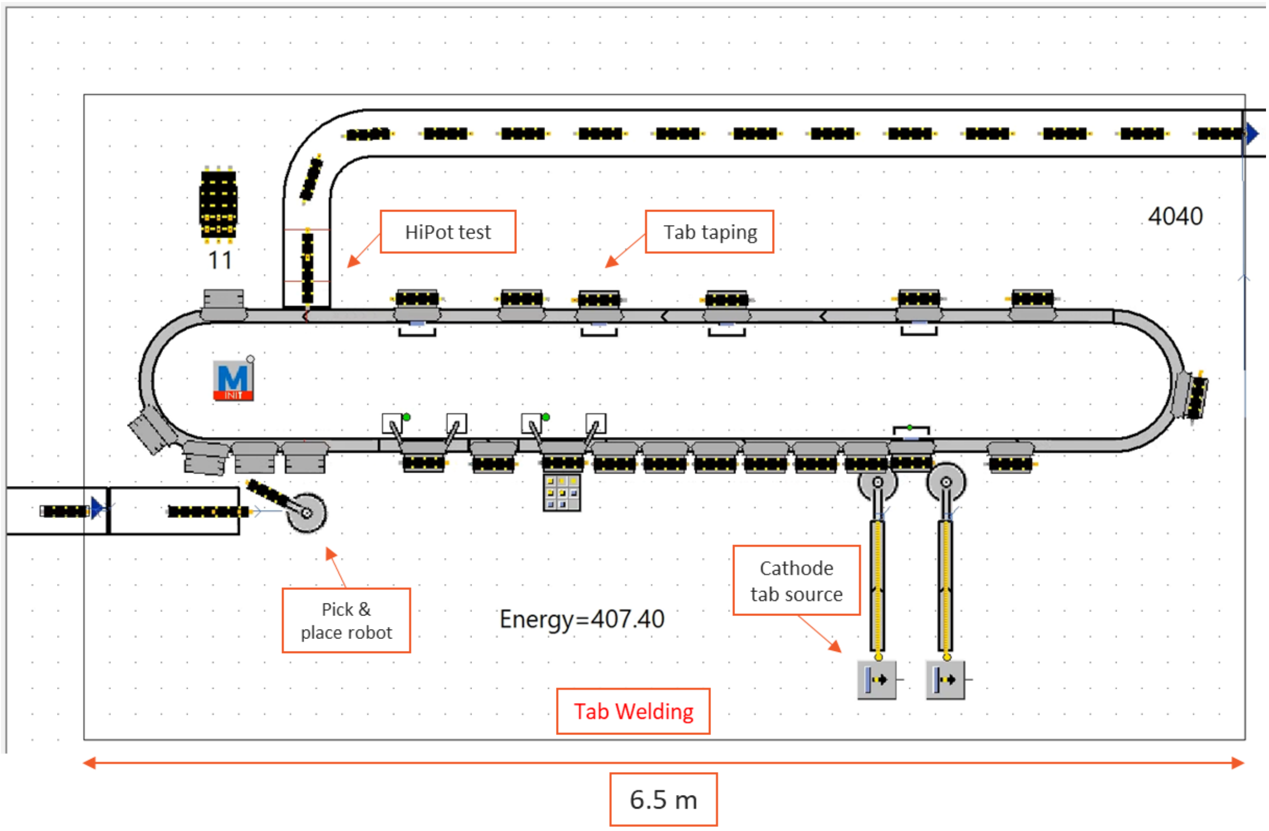

Figure 18: 2D simulation of tab trimming and welding machines

The deep drawing and packaging (DDP) machine comprise two main sub-units, namely deep drawing of pouch foil, and cell packaging units, as shown in Figure 19. First, the pouch foil is cut into the 3beLiEVe dimension, then it is deep drawn. The deep-drawn pouch bags are placed on the nests that carry them to the following stations. After trimming and pouch inspections, the faulty pouches are removed, and the sound ones go on to accommodate the cells coming from the tab welding unit. Afterward, the nests close, and the pouches are sealed, trimmed, and passed through a vision system for the final inspection. In the end, the successfully packaged cells go to the electrolyte filling unit via a robot handling system.

In the electrolyte filling unit, the cells are placed into a cell carrier with a pick and place robot. The cells are individually weighed and dry-tested. A set of carriers containing cells builds up a buffer in front of the vacuum chamber of the filling station. Then, the cells are loaded into the filling chamber, evacuated, filled with a certain dose of electrolyte, and sealed from the top side of the gas pouch. After electrolyte filling, the cells are weighed again one by one before undergoing a wet test. Eventually, the cells are unloaded using a pick and place robot and placed into a pallet known as a formation carrier to be transferred to the formation unit.

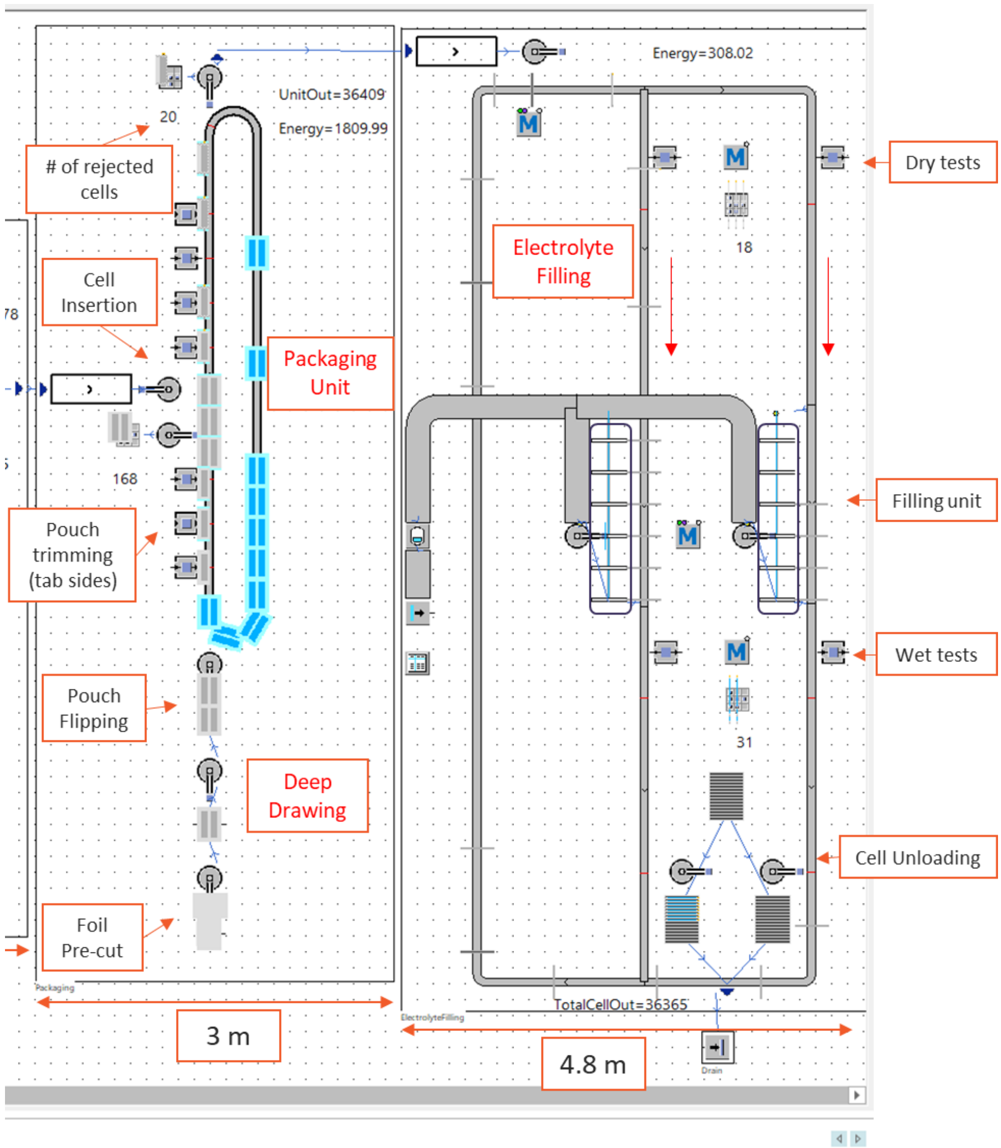

Figure 19: 2D simulation of a) deep drawing and packaging and b) electrolyte filling machines

3.2.1. Material flows and energy consumption

The electrode reels are treated with a 24 h final drying process in 3 vacuum ovens before being introduced in the dry-room. The operation of the dry-room, with its air conditioning and dehumidifying units, requires an estimated load of 246 kW and consumes of 1.55 GWh/year.

The electrode coils are then later notched by anode and cathode notching machines. Each machine notches on average 491.17 cells per minute, hitting 164 strokes per minute with a triple notching tool. In the notching process, part of the bare foil is cut from the electrode and constitutes scrap metal that is collected and recycled. The detailed materials flow and process rates are exposed in Table 28. The electrical power load for the two notching machines is estimated to be 5.2 kW, determining an energy consumption of 0.03 GWh/year.

Anode		Cathode	
Machines	1	**Machines**	1
Quantities per machine			
Electrode in m/h	2631.95	**Electrode in m/h**	2576.54
Electrode in mm/s	731.10	**Electrode in mm/s**	715.71
Total cells notched per minute	461.75	**Total cells notched per minute**	461.75
Copper barefoil scrap out kg/h	4.44	**Aluminum barefoil scrap out kg/h**	1.94
Average Power kW	2.6	**Average Power kW**	2.6

Table 28 Materials flow and rate of the notching machines.

Lamination and stacking is performed with two Monocell Lamination and Stacking machines (Manz code MLS); the overall material flow rates and parts produced per hour are shown in Table 29. The two machines require an average total power of 84 kW and contribute 0.53 GWh/y to the factory energy consumption.

Machines	**2**
Quantities per machine	
Anode in mm/s	356.72
Cathode in mm/s	349.21
Separator 1 in mm/s	376.70
Separator 2 in mm/s	376.70
Belt protector 1 film in mm/s	376.70
Belt protector 2 film in mm/s	376.70
Anode cut electrodes/h	13517.95
Cathode cut electrode/h	13517.95
Not OK monocells out/h	270.36
OK monocells out/h	13247.59
Stacks out/h	287.99
Average Power kW	42

Table 29 Materials flow and speed of the lamination and stacking machines.

The taping process that follows lamination and stacking is performed by one machine, applying 6 strips of tape to each stack at the rates reported in Table 30; the average power load is 6 kW and the energy consumption 0.04 GWh/y.

Machines	**1**
Quantities per machine	
stacks in /min (ppm)	9.60
failed stacks/h	5.76
OK stacks out/h	570.22
Average Power kW	6

Table 30 Materials flow and speed of the taping machines.

Following the taping station, the tab trimming and welding station welds the monocells in the stack to the external tab (current collector); the rate of product flow is shown in Table 31. This process requires 30 kW of electric power on average and amounts to 0.19 GWh/year of energy consumption.

Machines	1
Quantities per machine	
stacks in /min (ppm)	9.50
failed stacks/h	11.40
OK stacks out/h	558.82
Average Power kW	30

Table 31 Materials flow and process rate at the tab trimming and welding stations.

The deep drawing and packaging process is carried out by one machine with the rates shown in Table 32, using a total average power of 40 kW and consuming 0.25 GWh/year.

Machines	1
Quantities per machine	
stacks in /min (ppm)	9.31
failed stacks/h	11.18
OK pouch bags out/h	547.64
Average Power kW	40

Table 32 Materials flow and process rate for the deep drawing and packaging stations.

The final process in cell assembly, electrolyte filling, is performed by one machine; the total rate of electrolyte consumption and pouch bag filling is shown in Table 33. The total average load of 30 kW contributes 0.19 GWh/year in energy consumption.

Machines	1
Quantities per machine	
cells in /min (ppm)	9.13
electrolyte in L/h	43.96
failed cells/h	10.95
OK filled cells out/h	536.69
Average Power kW	30

Table 33 Materials flow and process rate for the electrolyte filling stations.

3.3. Cell Finishing

Cell finishing is associated with processes required to electrochemically activate the battery cell. It is essentially the longest process in the whole value chain of Li-ion battery manufacturing.

Trays containing the electrolyte-filled pouch cells are introduced from the dry room to the cell finishing area. First, the trays are transferred to the tray exchange area where the trays are replaced with clamped ones. The pouch bags filled with electrolyte first undergo a H.T. aging step to help achieve a complete electrolyte soaking. Then cells are pre-charged and cycled with formation charge-discharge cycles to form stable interfaces between electrodes and electrolyte. The gas that is formed in the first charge cycles and accumulates in the pouch bag is removed by the degassing stations. The cells then undergo a second aging step at room temperature, after which they are graded by measuring their actual capacity through further charge-discharge cycles. The defective cells are discarded while the other cells are transferred to the module assembly area. Pre-charging and formation steps usually require hours to be completed, while aging is normally carried out over days, therefore all these processes area carried out inside warehouse structures. Figure 20 shows the 2D layout of the simulated cell finishing processes. It is noteworthy that among the steps involved in the cell finishing processes, “Tray Exchange” and “Rework/Cell Removal” are carried out manually with the help of workers while all the other processes are entirely automated.

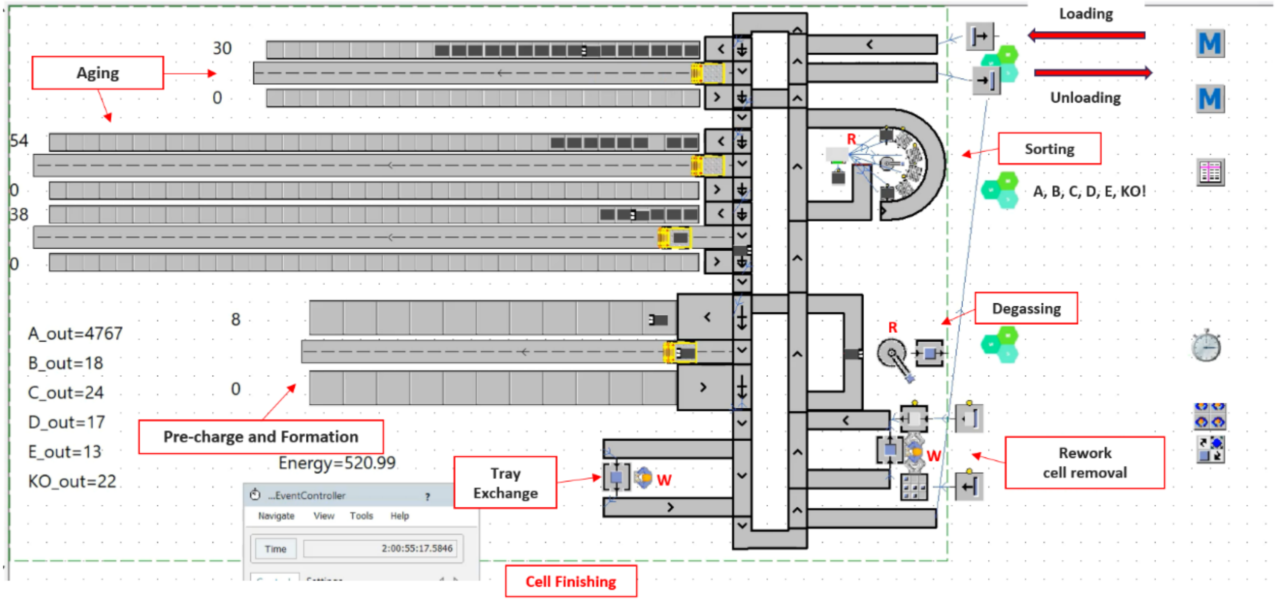

Figure 20: 2D simulation of cell finishing processes

Figure 21 summarizes the three main production zones of the factory producing 3beLiEVe pouch cells (analogous to the main processes listed in Figure 2). Cell assembly processes take place inside the dry room atmosphere distinguished by dashed lines.

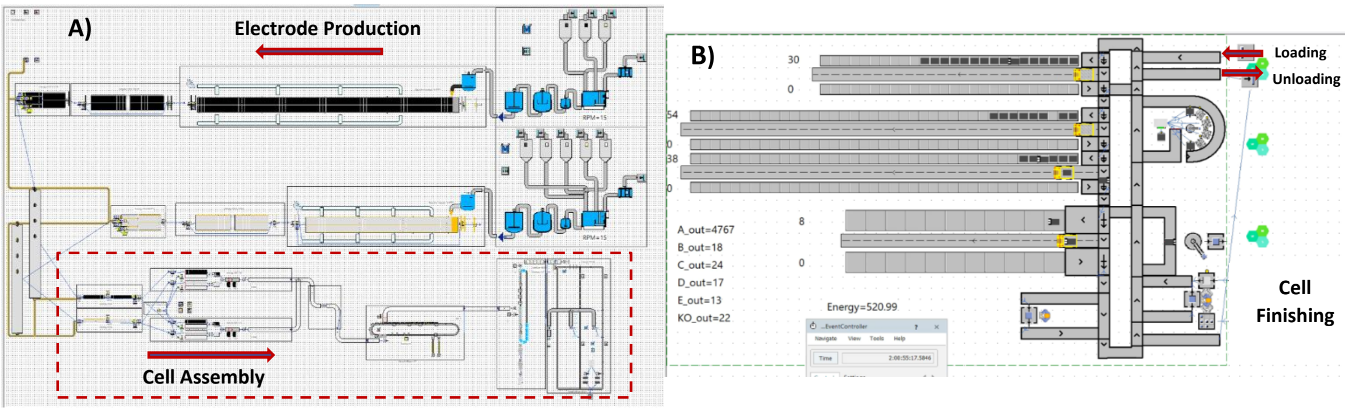

Figure 21: Production areas of 3beLiEVe battery cell manufacturing (a) Electrode production and cell assembly lines; (b) Cell finishing

3.3.1. Material flows and energy consumption

In the cell finishing part of the plant, the cells are transported inside trays that have a capacity of 32 cells. Aging, pre-charging and formation are long processes that are carried out inside warehouses, while degassing and grading are performed by discrete machines. The capacity of warehouses, and their energy consumption are reported in Table 34,Table 35, and Table 36, respectively.

High Temperature Aging	
cells in/h	536.69
failed cells/h	0
OK cells out/h	536.69
Trays n.	202
Surface m²	9
Average Power kW	8.62
Pre-charging & Formation	
cells in/h	536.69
failed cells/h	5.37
OK cells out/h	531.32
Trays n.	319
Surface m²	14
Average Power kW	1652.58
Room temperature aging	
cells in/h	526.01
failed cells/h	0
OK cells out/h	526.01
Trays n.	2762
Surface m²	118
Average Power kW	23.57

Table 34 Capacity, flow of materials and power absorbed by warehouses in cell finishing.

Machines	**1**
Quantities per machine	
cells in /min (ppm)	8.86
failed cells/h	5.31
OK cells out/h	526.01
Average Power kW	30

Table 35 Capacity of degassing stations and flow rate of materials.

cells in/h	**526.01**
not OK cells out/h	10.52
OK cells out/h	515.49
Trays n.	33
Average Power kW	161.97

Table 36 Flow rate of materials at the cell grading stations.

The model estimated for high temperature aging warehouse an electric load of 8.6 kW and an energy consumption of 0.05 GWh/year. The pre-charging and formation phase requires an average power load of 1652 kW, determining an energy consumption of 10.4 GWh/year. The degassing stations have an average power load of 30 kW, consuming 0.19 GWh/year. The room temperature aging warehouse is estimated to require 24 kW and consume 0.15 GWh/year. Finally, the grading and sorting stations are estimated to absorb 162 kW and consume 1 GWh/year.

3.4. Machine failure analyses

An efficient material flow in a series production requires precise prediction of machine states and the effect of each state on the whole performance of the other machines.

In this modeling activity, a randomly distributed machine failure was incorporated into the model such that the state of each machine can be monitored during the operation and in case of any failure, the eventual effect on the other machine can be precisely addressed. Four machine states were considered including “working”, “waiting”, “blocked” and “failed”. Failure includes times for retooling, maintenance, accidents, machine failures, etc. As a result, machine availability and the mean time to repair (MTTR) were defined for each machine. The availability was defined as the ratio between the mean time between failures (MTBF) divided by the sum of the MTBF and MTTR. Figure 22 summarizes the machine states in the cell assembly line independent of the electrode production and cell finishing lines.

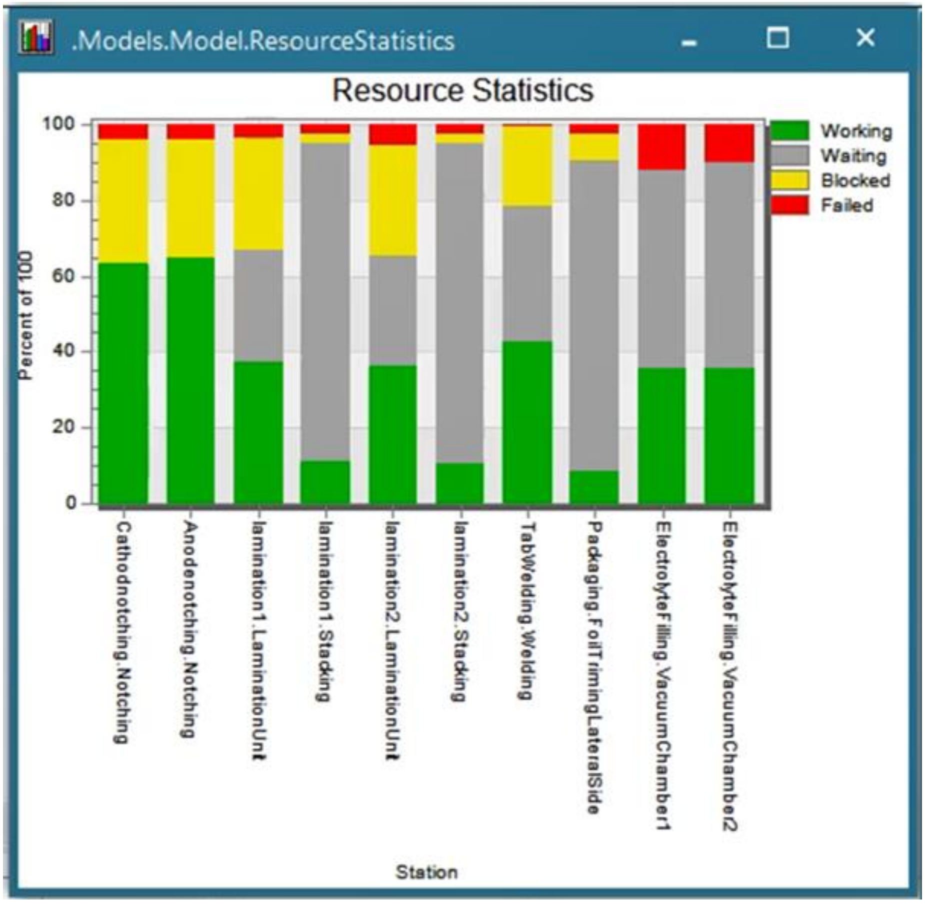

Figure 22: Simulation of machine states in cell assembly

3.5. 3D simulation

3D simulation of processes is a helpful tool to address the complex interaction between sub-systems and to include more details and process parameters during the phase of factory planning. This activity was aimed at showing how the model can be extended to 3D. Eventually, the full 3D simulation of the cell manufacturing processes is envisaged as an extension of the 3beLiEVe project in the future.

3.5.1. Cell assembly (notching machine)

Among the cell assembly processes, the electrode notching process was taken as an example to be modelled in 3D. The Fast Electrode Notching machine (Manz code name FEN) was modelled in Tecnomatix for the 3beLiEVe virtualization task (Figure 23).

A 3D model of the notching machine was created in Tecnomatix. The moving parts of the machine including reel holders, notching tool, etc. as well as the flow of material were animated. The auto-splicing concept was modelled by using a parallel station for both unwinding and rewinding. An automated guided vehicle (AGV) was adopted to transport coils of cathodes and anodes from the dryers to the unwinding unit of the notching machine and to move the rewound notched coils from the notching machine to the lamination and stacking machine. The worker pool was defined, as a worker carries out mounting of the coil on the reel holder in the unwinding unit as well as removing the notched coils of electrodes.

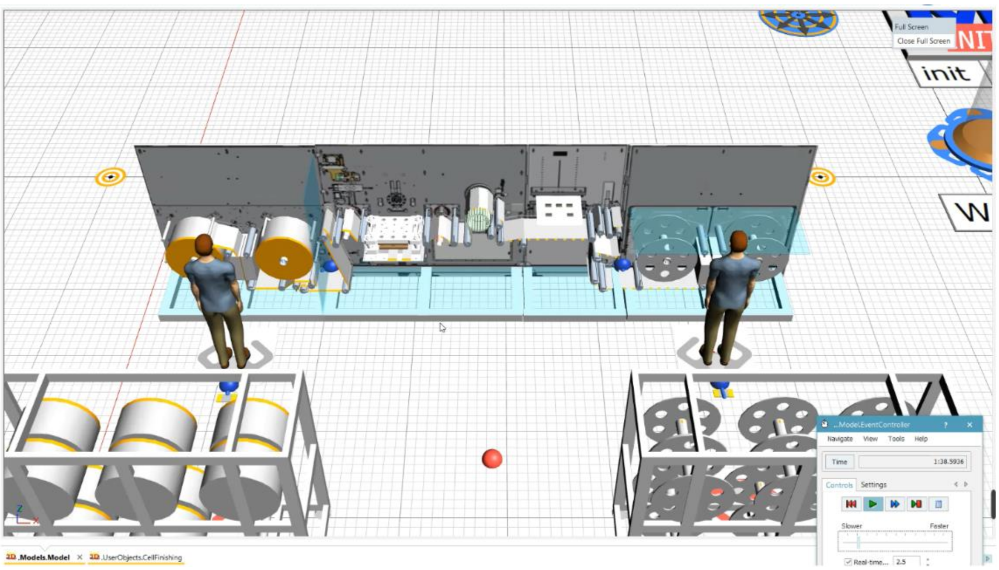

Figure 23: 3D simulation of electrode notching

3.5.2. Cell finishing

A 3D simulation of the cell finishing processes was carried out as shown in Figure 24. The formation and aging areas were simulated in 3D with as a high-bay warehouse (HBW) equipped with a warehouse management system (WMS) where stacker cranes moving on rails pick each tray at the entrance and place it in the corresponding rack. Based on the demand by other units they deliver the tray to the conveying system that connects all these units.

Figure 24: 3D simulation of cell finishing

4. Simulation of cell manufacturing processes in a 10 GWh/year plant

The 10 GWh/year pouch cell production factory produces about 32.5 million quality cells per year (5155 per hour) and extends over a surface of 80,000 m^2. Differently from the 1 GWh/year plant, the slurry mixing process was changed from batch to continuous mixing, the latter being more convenient from the point of view of capital and operational expenditure. The widths of the jumbo reels were doubled compared to the ones of the 1 GWh/year plant to support the increased throughput requirements. The number of machines installed and the number of operators working per shift is shown in Table 37; a 3D layout of the factory is shown in Figure 25. The quality of production achieved at different manufacturing steps is reported in Table 38, while a view of the energy consumed by the factory is given in Table 39.

	Machines	**Operators**
Anode mixing	2	2
Anode coating & drying	2	2
Anode calendering	2	2
Anode slitting	2	2
Anode final drying	6	1
Total Anode manufacturing	**14**	**9**
Cathode mixing	3	3
Cathode coating & drying	3	3
Cathode calendering	3	3
Cathode slitting	3	3
Cathode final drying	12	2
Total Cathode manufacturing	**24**	**14**
Total electrode manufacturing	**38**	**23**
Anode notching	10	10
Cathode notching	10	10
Lamination and stacking	20	40
Taping	8	8
Tab trimming and welding	8	8
Deep drawing & packaging	8	8
Electrolyte filling	8	8
Total cell assembly	**72**	**92**
High temperature aging	1	1
Pre-Charging & Formation	1	1
Degassing	8	8
Room temperature aging	1	1
Grading & Sorting	1	1
Total cell finishing	**12**	**12**
TOTAL MANUFACTURING PLANT	**122**	**127**

Table 37 Number of machines installed in the 10 GWh/year plant and workers per shift.

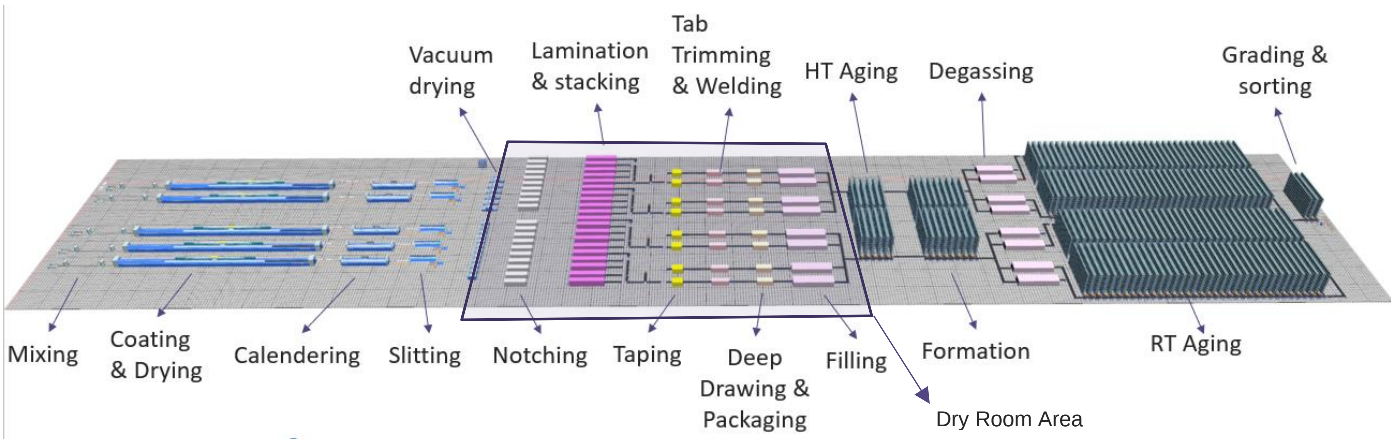

Figure 25 View of the 10 GWh/year manufacturing plant.

Anode manufacturing quality	**97.6%**
Cathode manufacturing quality	97.6%
Cell assembly quality	91.3%
Cell finishing quality	96.0%
Overall cell production quality	85.6%

Table 38 Quality of products at different stages of the 10 GWh/year plant.

Electrode Manufacturing	**110.1**	GWh/y
Cell assembly	11.0	GWh/y
dry room	9.1	GWh/y
conveyor belts	0.5	GWh/y
Cell finishing	117.9	GWh/y
Coil handling	0.6	GWh/y
Building consumption (200 W/m2)	115.2	GWh/y
Total energy consumption from cell manufacturing	**364.3**	GWh/y
Energy consumption per unit of product	**36.4**	Wh/Wh of product

Table 39 Energy consumption of the 10 GWh/year plant.

4.1. Electrode Production

The 10 GWh/year plant features two anode manufacturing lines and three cathode manufacturing lines, which allows a more rational use of space thanks to the similar lengths of the anode and cathode ovens (Section 2.2.2). Each line contains a continuous mixing machine, a coating and drying machine, a calendering machine, and a slitting machine.

4.1.1. Material flows and energy consumption

The average material flow and slurry production rates have been scaled up for the 10 GWh/year production scale (Table 40).

Anode		Cathode	
Machines	2	**Machines**	3
Quantities per machine			
Solids in kg/h	624.44	**Solids in kg/h**	1189.44
Graphite kg/h	477.70	LMNO kg/h	1067.30

Silicon kg/h	84.30	Carbon black kg/h	59.29
Carbon black kg/h	11.96	Binder 1 (LBG) kg/h	23.72
CMC kg/h	11.96	Additive (2150) kg/h	3.56
SBR kg/h	11.96	Binder 2 (PVDF) kg/h	35.58
Solvents in	936.66	**Solvents in kg/h**	534.39
DI Water slurry kg/h	560.34	NMP slurry kg/h	0.00
DI Water CMC kg/h	361.71	NMP (PVDF) kg/h	320.19
DI Water SBR kg/h	14.61	NMP Total kg/h	320.19
DI Water total kg/h	936.66	Acetone kg/h	214.20
Total in kg/h	1561.10	Total in kg/h	1723.83
Slurry out kg/h	1557.98	**Slurry out kg/h**	1720.38
Slurry out L/h	1220.35	**Slurry out L/h**	900.42
Slurry waste kg/h	3.12	**Slurry waste kg/h**	3.45
Average Power kW	87.42	**Average Power kW**	96.53

Table 40 Material flow rates for the slurry mixing calculated for 10 GWh/year cell production.

The estimated average power load of all mixing equipment for anode and cathode is 464 kW, resulting in an energy consumption of 0.29 GWh/year. Compared to the batch mixing process used in the 1 GWh/year, the continuous process is about 4 times more energy efficient.

The coating and drying machine takes slurry from the mixing machine and metal foil that is unwound from "jumbo" coils with a width of 1390 mm and 1382 mm for anode and cathode respectively. During drying, the solvent contained in the slurry evaporates and is recovered. The material flow rates in the coating and drying process are reported in Table 41.

Anode		**Cathode**	
Machines	2	**Machines**	3
Quantities per machine			
Slurry in kg/h	1557.98	**Slurry in kg/h**	1720.38
Copper foil in m/h	3329.75	**Aluminum foil in m/h**	2173.10
Copper foil in m/min	55.50	**Aluminum foil in m/min**	36.22
Copper foil in kg/h	414.70	**Aluminum foil in kg/h**	121.63
Solvent out kg/h	932.92	**Solvent out kg/h**	532.25
Copper foil waste kg/h	0.83	**Aluminum foil waste kg/h**	0.24
Slurry waste kg/h	3.12	**Slurry waste kg/h**	3.44
Average Power kW	3000	**Average Power kW**	3000

Table 41 Material flow rates at the coating and drying machine of the 10 GWh/year plant.

Coating and drying of anode and cathode is estimated to require an overall average power load of 15,000 kW, resulting in an energy consumption of 94.5 GWh/year.

The material flow rates for the calendering and slitting machines are shown in Table 42 and Table 43. During the slitting process, each "jumbo" coil is split into 4 "daughter" coils.

Anode		**Cathode**	
Machines	2	**Machines**	3
Quantities per machine			
Electrode in m/h	3323.09	**Electrode in m/h**	2168.75
Electrode in m/min	55.38	**Electrode in m/min**	36.15
Electrode in kg/h	1035.82	**Electrode in kg/h**	1306.08
Electrode waste kg/h	5.18	**Electrode waste kg/h**	6.53

Average Power kW	270	**Average Power kW**	270

Table 42 Material flow rates for the calendering machine in the 10 GWh/year plant.

Anode		**Cathode**	
Machines	2	**Machines**	3
Quantities per machine			
Electrode in m/h	3306.47	**Electrode in m/h**	2157.91
Electrode in m/min	55.11	**Electrode in m/min**	35.97
Electrode in kg/h	1030.64	**Electrode in kg/h**	1299.55
Electrode waste kg/h	5.15	**Electrode waste kg/h**	6.50
Average Power kW	44	**Average Power kW**	44

Table 43 Material flow rates for the slitting machine in the 10 GWh/year plant.

The overall power load required by the calendering machines of the anode and cathode lines is 1350 kW, resulting in an energy consumption of 8.5 GWh/year. The average power demanded by the 5 slitting machines corresponds to 220 kW, determining an energy consumption of 1.4 GWh/year.

4.2. Cell assembly

The cell assembly line in the 10 GWh/year plant features 20 notching machines, 10 for the anode and 10 for the cathode, followed by 20 lamination and stacking machines. The subsequent steps are carried out by 16 taping machines, 16 tab trimming and welding machines, 16 deep drawing machines and 16 electrolyte filling machines.

4.2.1. Material flows and energy consumption

The additional vacuum drying performed before entering the dry room using 20 ovens, requires an electrical load of 500 kW and energy consumption of 3.15 GWh/year. The electric power load of the dry-room is on average 2119 kW, resulting in an energy consumption of 13.4 GWh/year.

The electrode coils processed by the slitting machines are later processed by anode and cathode notching machines. Each of the 20 machines notches on average 461.75 cells per minute, hitting 154 strokes per minute with a triple notching tool, as in the 1 GWh/year plant. The detailed materials flow and process rates are displayed in Table 44. The electrical power load for the 20 notching machines is estimated to be 52 kW, resulting in an energy consumption of 0.33 GWh/year.

Anode		**Cathode**	
Machines	10	**Machines**	10
Quantities per machine			
Electrode in m/h	2631.95	**Electrode in m/h**	2576.54
Electrode in mm/s	731.10	**Electrode in mm/s**	715.71
Total cells notched per minute	461.75	**Total cells notched per minute**	461.75
Copper bare foil scrap out kg/h	4.44	**Aluminum bare foil scrap out kg/h**	1.94
Average Power kW	2.6	**Average Power kW**	2.6

Table 44 Materials flow and rate of the notching process for the 10 GWh/year plant.

In the dry room the cell stacks are produced by 20 Mono-cell Lamination and Stacking machines, with overall material flow rates and part produced per hour shown in Table 45. The power absorbed is on average 840 kW in total and contribute 5.3 GWh/year to the factory energy consumption.

Machines	20
Quantities per machine	
Anode in mm/s	356.72
Cathode in mm/s	349.21
Separator 1 in mm/s	376.70
Separator 2 in mm/s	376.70
Belt protector 1 film in mm/s	376.70
Belt protector 2 film in mm/s	376.70
Anode cut electrodes/h	13517.95
Cathode cut electrode/h	13517.95
Not OK mono-cells out/h	270.36
OK mono-cells out/h	13247.59
Stacks out/h	287.99
Average Power kW	42

Table 45 Materials flow and rate of the lamination and stacking process in the 10 GWh/year plant.

The taping process that follows lamination and stacking is performed by set of 7 machines, applying 6 strips of tape to each stack at the rates reported in Table 46; the overall power load is 42 kW, resulting in an energy consumption of 0.26 GWh/year.

Machines	7
Quantities per machine	
stacks in /min (ppm)	13.71
failed stacks/h	8.23
OK stacks out/h	814.60
Average Power kW	6

Table 46 Materials flow and rate of the taping process.

Following the taping station, the tab trimming and welding station welds the mono-cells in the stack to the external tab (current collector); the rate of product flow is shown in Table 47. This process requires 210 kW of electric power on average and amounts to 1.3 GWh/year of energy consumption.

Machines	7
Quantities per machine	
stacks in /min (ppm)	13.58
failed stacks/h	16.29
OK stacks out/h	798.31
Average Power kW	30

Table 47 Materials flow and process rate at the tab trimming and welding stations.

The deep drawing and packaging process is carried out by 7 machines (Table 48), using a total average power of 280 kW and consuming 1.8 GWh/year.

Machines	7
Quantities per machine	
stacks in /min (ppm)	13.31
failed stacks/h	15.97
OK pouch bags out/h	782.35
Average Power kW	40

Table 48 Materials flow and process rate for the deep drawing and packaging station.

The final process in cell assembly, electrolyte filling, is performed by 7 machines; the total rate of electrolyte consumption and pouch bag filling is shown in Table 49. In this case the average load is 210 kW and the energy consumption 1.3 GWh/year.

Machines	**7**
Quantities per machine	
cells in /min (ppm)	13.04
electrolyte in L/h	62.80
failed cells/h	15.65
OK filled cells out/h	766.70
Average Power kW	30

Table 49 Materials flow and process rate for the electrolyte filling station.

4.3. Cell Finishing

The cell finishing area is structured similarly to the 1 GWh/year plant and uses the same type of machines. Warehouses have been upgraded to provide the necessary capacity, while the number of discrete machines has been increased accordingly.

4.3.1. Material flows and energy consumption

In the cell finishing part of the plant, the cells are transported inside trays that have a capacity of 32 cells. Aging, pre-charging and formation are long processes that are carried out inside warehouses, while degassing and grading are performed by discrete machines. The capacity of warehouses, and their energy consumption are reported in

High Temperature Aging	
cells in/h	5366.89
failed cells/h	0.00
OK cells out/h	5366.89
Trays n.	2013
Surface m²	86
Average Power kW	85.89
Pre-charging & Formation	
cells in/h	5366.89
failed cells/h	53.67
OK cells out/h	5313.22
Trays n.	3187
Surface m²	136
Average Power kW	16525.82
Room temperature aging	
cells in/h	5260.09
failed cells/h	0
OK cells out/h	5260.09
Trays n.	27616
Surface m2	1178
Average Power kW	235.66

Table 50. The degassing and grading operations are performed on cells at speeds indicated in

Machines	**7**
Quantities per machine	
cells in /min (ppm)	12.65
failed cells/h	7.59
OK cells out/h	751.44
Average Power kW	30

Table 51 and

cells in/h	**5260.09**
not OK cells out/h	105.20
OK cells out/h	5154.88
Trays n.	329
Average Power kW	1619.70

Table 52 respectively.

High Temperature Aging	
cells in/h	5366.89
failed cells/h	0.00
OK cells out/h	5366.89
Trays n.	2013
Surface m²	86
Average Power kW	85.89
Pre-charging & Formation	
cells in/h	5366.89
failed cells/h	53.67
OK cells out/h	5313.22
Trays n.	3187
Surface m²	136
Average Power kW	16525.82
Room temperature aging	
cells in/h	5260.09
failed cells/h	0
OK cells out/h	5260.09
Trays n.	27616
Surface m2	1178
Average Power kW	235.66

Table 50 Capacity, flow of materials and power absorbed by warehouses in cell finishing in the 10 GWh/year plant.

Machines	**7**
Quantities per machine	
cells in /min (ppm)	12.65
failed cells/h	7.59
OK cells out/h	751.44
Average Power kW	30

Table 51 Capacity of degassing stations and flow rate of materials in the 10 GWh/year plant.

cells in/h	**5260.09**
not OK cells out/h	105.20
OK cells out/h	5154.88

Trays n.	329
Average Power kW	1619.70

Table 52 Flow rate of materials at the cell grading stations in the 10 GWh/year plant.

For the high temperature aging warehouse, the model estimated an electric load of 86 kW and an energy consumption of 0.54 GWh/year. The pre-charging and formation phase requires an average power load of 16,526 kW, amounting to an energy consumption of 104 GWh/year. The degassing stations have an average power load of 210 kW, consuming 1.3 GWh/year. The room temperature aging warehouse is estimated to require 236 kW and consume 1.5 GWh/year. Finally, the sorting stations are estimated to absorb 1620 kW and consume 10.2 GWh/year.

5. Conclusions

The simulations performed at the level of a base production line of 1 GWh/y in 2D and partially in 3D have provided a significant insight into the complexity and extent of a battery production plant and the capability of the simulation tools in the plant design and management. The plant has a footprint of about 10,000 m^2 and produces on average 515 good quality cells per hour, with an overall energy consumption of 49.9 Wh per Wh of cell energy capacity. From slurry mixing to cell sorting, the number of installed machines is 24, excluding AGV units.

The scale-up of this model to a full 10 GWh/y production plant has led to the rearrangement of the electrode production part, that has changed from batch mixing to continuous mixing and uses wider “jumbo” electrode reels with a width of about 1400mm. These adjustments resulted in a more efficient use of equipment, plant space and processing time as highlighted by the detailed analysis of the simulation. The increase in energy efficiency from the 1 GWh/y to 10 GWh/y plant deriving from scaling up of the equipment has led, according to initial hypothesis in section 2.2, to a reduction of the energy consumption from 49.9 to 36.3 Wh per Wh of cell capacity produced; the required areal footprint per GWh/y decreased from 10,000 m^2 to 8,000 m^2.

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