Battery Packaging – Technology Review

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Abstract. This paper gives a brief overview of battery packaging concepts, their specific advantages and drawbacks, as well as the importance of packaging for performance and cost. Production processes, scaling and automation are discussed in detail to reveal opportunities for cost reduction. Module standardization as an additional path to drive down cost is introduced. A comparison to electronics and photovoltaics production shows “lessons learned” in those related industries and how they can accelerate learning curves in battery production.

Keywords: Battery Packaging, Production, Processes, Process Equipment, Engineering, Backend Design, Standardization, Lithium Ion.
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INTRODUCTION

Although worldwide battery demand today is mostly driven by automotive starter batteries, portable computers and cell phones, high-power applications like electric vehicles (EV) or storage for renewable energy set the scene for the latest interest in rechargeable battery technology. Reliability and cost are drivers for success. Besides innovations in cell chemistries and package design the alteration from low volume manufacture to mass production is one of the grand challenges in bringing high-power batteries into viable markets. Design for manufacturability, production processes and equipment as well as factory automation play a vital role in achieving this goal.

Different cell chemistries basically define the essence of a battery and lay the foundations for its suitability for a specific application – from consumer to industrial, from stationary to mobile, optimized for high power or high energy. Despite this important electrochemical background, however, it is the packaging that greatly influences important performance parameters like lifetime, cyclability, ruggedness, safety and – most of all – cost. Overall, packaging adapts the battery to the specific needs of an application: sealing, form factor, temperature and charge monitoring as well as overall management are determined by the design and make of cells, modules and packs. Especially for lithium ion chemistries a battery management system is essential to create a reliable, lasting and safe battery – it is thus an important part of the package.

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Packaging technology involves several levels: The smallest unit of a battery is the electrochemical cell, consisting of a cathode and an anode embedded in an electrolyte for ion migration. An insulating separator between cathode and anode prevents short circuits. Small batteries, *e.g.* for consumer applications like flashlights, remote controls, *etc.*, just consist of one electrochemical cell – therefore the packaging on cell level already defines the outward appearance. For higher voltages or higher capacities several electrochemical cell units are connected in parallel or in series, or both. Lithium ion cathode-separator-anode stacks or jelly rolls are still called "*cells*". Several of these cells are connected to *modules*, which contain individual cell monitoring and temperature control. The assembly of modules form a *battery pack* (Fig. 1).

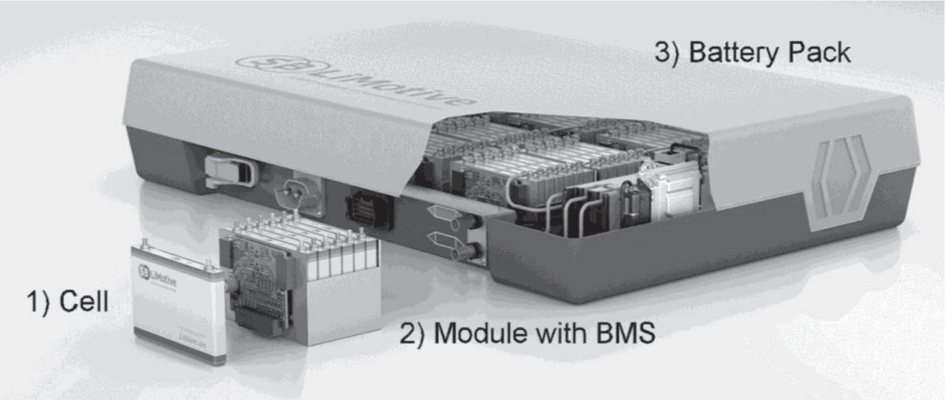

FIGURE 1. Example for packaging of a high-power automotive traction battery: (1) shows a prismatic lithium-ion cell package. Several of these cells are put together to form modules (2). They are assembled with a battery management system (BMS), thermal management, and electronic components to form a battery pack (3). The battery management system monitors the cells and the battery, continuously controlling current and voltage, as well as temperature and charge status. Reprinted with permission of Robert Bosch GmbH.

PACKAGING TECHNOLOGY

Cell packaging designs and their combinations in modules and battery packs are offered in a huge variety, for primary and secondary batteries, and for different applications. The aim of this paper is not to give a comprehensive overview, since this is already done elsewhere, *e.g.* [1,2,3] and references therein. We focus on the most common examples for packaging technology, processing and manufacturing issues with special emphasis on high power / high energy secondary batteries, especially with lithium ion (Li-ion) chemistries.

Cell Packaging Concepts

All basic concepts of cell packaging are given in [1]. A good overview of historical cell packaging concepts and the year of their introduction is given in [2]. A comprehensive insight into standardisation of cell packages used in common primary and secondary battery types for consumer and light industrial use is given in [3].

Cylindrical Cell

The ***cylindrical*** packaging design was an early form of mass-produced batteries and is still very popular today. The biggest advantage is the mechanical stability of the cylinder, which naturally withstands internal pressures without deformation. A first standard introduced already in 1896 was the big F-cell originally used for lanterns. As form factors became smaller, new standards were created with letters counting upwards: D, C, AA, and AAA are still very common today for all kinds of consumer-type applications (Fig. 2). Secondary batteries of those packaging types use mostly Nickel-Cadmium (NiCd) and Nickel-Metal-Hydride (NiMH) chemistries. They contain one electrochemical cell.

FIGURE 2. Common consumer type battery packages, from left to right: a large 4.5 Volt battery, a D-cell, a C-cell, an AA-cell, an AAA-cell, an AAAA-cell, an A23 battery, a 9 Volt (PP3) battery, and a pair of button cells (CR2032 and LR44). Picture and caption reprinted from [3].

Although not widely used today, some manufacturers chose cylindrical packages even for lead-acid batteries (Fig. 3). A package with small, cylindrical lead-acid cells containing spirally-wound electrodes equivalent in size to the conventional D-cell resulted from research started in 1967. These cells were the first to use a separator material consisting of microfiber glass paper, now generally referred to as “absorbent glass mat” (AGM). The first commercially available AGM cell on the market was the Cyclon, patented by Gates Rubber Corporation in 1972 and now produced by Enersys [4]. The electrolyte is held in the glass mats, as opposed to freely flooding the plates. This configuration significantly increases packaging density in the cell, especially with spiral winding of the cells [5]. This way, breaking of the plates does not occur so easily compared to the flooded type, which makes AGM lead-acid batteries very attractive for rugged environments where vibrations or high accelerations occur, *e.g.* in industrial robots, military, construction machines, motorsports, *etc.*

FIGURE 3. Cylindrical lead-acid batteries. Left: Cyclon was the first commercially available AGM lead-acid battery. Picture: Enersys. Right: Spiral-cell lead-acid with different terminal configuration built in a rectangular case to Battery Council International (BCI) specifications. Reprinted with permission of Johnson Controls Autobatterie GmbH & Co. KGaA.

As a result of higher packaging density, AGM lead-acid batteries have a low internal resistance, can deliver high currents and promise a relatively long service life, as well as deep-cycle stability. With the electrolyte soaked in the glass mats, they also withstand low temperatures more easily [6]. With start-stop features and higher energy requirements in modern cars, AGM will probably become more popular in the future. All the positive effects, however, come at a higher manufacturing cost.

On the Li-ion side a standard differing from the above mentioned consumer-type cell sizes (F to AAAA) for cylindical packaging was established in the mid 1990s: the 18650 cell, 18 denoting the diameter, 65 denoting the length im millimeters. It has a total mass of about 45 grams, including inactive material and packaging [7] and a capacity ranging from 1.2 to 3 Ah, depending on cell chemistry [2]. It contains one electrochemical cell, with cathode, anode and separator cut in stripes and rolled into a metal can. The 18650 and the larger formats derived from it are very common in battery packs for laptop PCs, electric bicycles and power tools. The packaging density when grouping cylindrical cells is low due to their round shape, and the cell case is comparatively heavy. However, air can easily circulate through a module or battery pack with cylindrical cells, which eases cooling.

Prismatic Cell

Whereas the packaging of, *e.g.*, consumer and starter batteries have been widely standardized, manufacturers of Li-ion batteries introduced new formats when requirements arising from product designs changed. This becomes obvious *e.g.* for mobile phones, digital still cameras, video cameras, or tablet computers. Batteries for those applications mostly have a box-like appearance called *prismatic*. There is no standard with respect to aspect ratio or size. Prismatic cells have also been chosen for high power applications like traction batteries for cars (Fig. 1). Older types of prismatic batteries also exist for above mentioned consumer batteries (4.5 V and 9 V examples in Fig. 2). Prismatic cells can contain one or more electrochemical cell units.

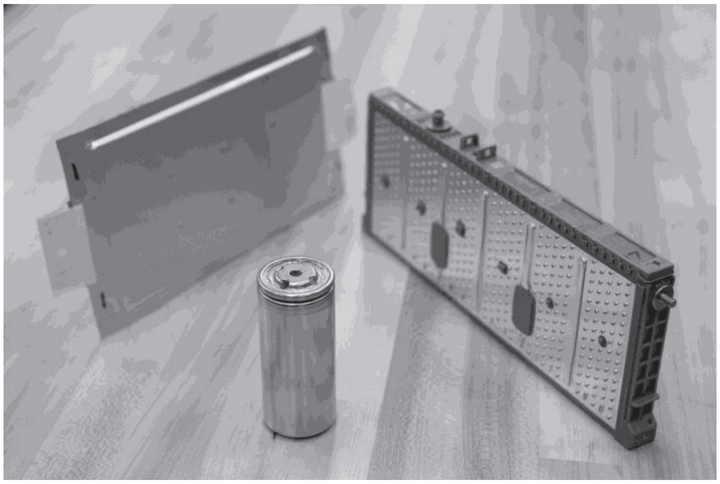

FIGURE 4. Three different sizes for Li-ion batteries (left to right): pouch cell, cylindrical cell, and prismatic cell, respectively. Reprinted with permission of Jeffrey Sauger, General Motors Corp.

For Li-ion prismatic cells, cathodes, anodes and separators are also manufacured in long stripes, wound up and then pressed to fit into the prismatic container. Compared to cylindrical cells, more stress is induced on the bent parts of the jelly roll in the corners, which can be a problem for the electrode coating or electrolyte distribution. The prismatic cell allows flexible design and improves packaging density in a module or pack. However, mechanical stress on the container is higher and thermal management becomes more complex than in a pack of cylindrical cells.

Pouch Cell

Pouch cells are a somewhat minimalistic approach to packaging, because they do not have a rigid container any more. In fact, they are only sealed by flexible foil, that is why they are also called “coffee bag cells”. Furthermore, cathodes, separators and anodes are stacked instead of wound. This approach increases packaging density to the maximum and saves weight, thus increasing energy density of the cell. This type of packaging is used only for Li-ion chemistries. Instead of a liquid electrolyte, a polymer electrolyte also acting as separator is sometimes used in this configuration. Pouch cells usually have more than one electrochemical cell inside.

These very flat cells perfectly fit *e.g.* into tablet computers (capacities around 4 Ah). They are also employed for high-power and for high-energy (EV) applications (capacity example: 20 Ah A5-size with 20 cathode, 20 anode and 40 separator sheets, respectively [8]). High currents either in charging or discharging mode result in internal pressure. Serious swelling of the package occurs when the cell is overheated or shortened. Swelling occurs as a normal process during the initial charging step (formation), though. To cope with that, manufacturers usually oversize the package, resulting in a separate “bag” to which excess gases can escape. After formation, the package is resealed to its final form, and the gas-bag is cut off. Nevertheless – more than prismatic cells, pouch cells need careful temperature management and support structures when placed into a module. There are no standard sizes so far.

From Cell to Module and from Module to Pack

The wording “battery module” is usually only used associated with high-power batteries. It denotes an assembly of cell packages, safety features like temperature, voltage and charge monitoring, as well as a battery management system (BMS), cooling / heating system and a base plate or housing.

Depending on the capacity or voltage needs of an application, cells are connected in parallel or in series. Parallel configuration adds capacity, leaving the voltage constant, serial configuration adds voltage, leaving the capacity constant, respectively. Already the electrochemical cell units in cell packs can be connected in series (example: 9 Volt “transistor radio” alkaline cell in Fig. 2 adding six 1.5 V AAAA-cell units, with capacity approximately 0.5 Ah) or in parallel (example: 20 Ah Li-ion pouch cell for automotive traction contains twenty 1 Ah units, with external voltage at around 3.6 V, depending on cathode and anode chemistry [8]).

A comprehensive overview on battery safety features is listed in [2]. Especially Li-ion cell configurations must contain electronic safety circuitry to prevent damage to the user [7]. Since the overall capacity and voltage of a module are defined by the weakest cell in the configuration, it is wise to monitor state of charge (SOC) and state of health (SOH), amongst other parameters already on cell level. Battery Management Systems provide this, combined with communication features to levelize charging and discharging, or even bypass bad cells. Tesla Motors, for example, use standard 18650 cells for their modules and put all their efforts of optimization into the BMS, rather than optimizing the cells [9, 10]. A BMS protects the battery by preventing it from running outside safe operation mode, such as over-current, over-voltage (during charging), under-voltage (during discharging), over-heating, under-cooling, or over-pressure. It is therefore a very important part of the module.

The difference between module and battery pack is the individual adoption to a certain application. Table 1 shows typical requirements for a variety of applications.

TABLE 1. Typical rechargeable battery applications: different levels of energy and power requirements set the scene for different cell chemistries and packaging (approximate values). For comparison: A typical 18650 Li-ion cell approximately delivers 10 Wh.

Application	Energy requirement [Wh]	Critical system requirements
Smartphone	5	Energy density
Laptop PC	50…100	Energy density
Hybrid Electric Vehicle (HEV)	1,000	Power and lifetime. Charging through recuperation, 0-5 km el. range
Plug-In Hybrid (PHEV)	5,000 … 10,000	Power and energy equally important, lifetime. Charging by grid and recuperation, 50-70 km el. range
Battery Electric Vehicle (BEV)	15,000 … 50.000	Energy, Depth of Discharge. Charging mostly by grid, 100-300 km el. range
Stationary battery buffering residential photovoltaics (PV) generator	5,000 … 10,000	Energy and lifetime. Average household consumption per day, charging by PV

Especially for large-scale applications (electric vehicles or renewable energy buffering) pack design is a differentiation factor for the battery integrators (*e.g.* car manufacturers). Therefore, standardization on battery pack level is hardly possible. On module level, however, standardization can be beneficial, as shown below.

PRODUCTION PROCESSES

Battery production starts with the *preparation of raw materials*, like the Li-metal-oxides and graphite, which have to be thoroughly ground, mixed and conditioned. Together with solvents they form a slurry of active material.

Second step is the *electrode production*, which involves coating of the active material slurry on top of metal sheets in a roll-to-roll process, followed by drying and compactation (called calendering).

The next step is the *cell production*. Slitting, separation, stacking or winding, contacting of the electrochemical cell units, packaging are the single processes employed here. Formation (initial charging) and ageing are important, but time consuming steps (24 hours and up to a month, respectively) to finalize cell production.

The last step in battery production is the *module and pack assembly*. Important *overall processes* are inspection and test, clean room and dry room technologies, line integration and automation.

The production of Li-ion batteries for high-power applications today is basically low volume manufacture. Producers work hard on increasing yields, reliability and process stability. However, inspection and test for all critical process steps are often missing. A continous in-line operation is not realised yet, mostly in cell production, due to roll-to-roll processing. Full automation is not economical as long as process yield is still a challenge and the market does not demand huge volumes. VDMA has set up a roadmapping process for the advancement of production solutions which gives an insight to the state of the art, and future developments in this field [11]. The roadmapping process is still ongoing. The results will be published elsewhere.

Although experience from the production of consumer batteries is not completely irrelevant to the production of traction batteries, these two product areas differ greatly both in terms of quality and lifetime (significant reduction in fault rate) and the production process itself (*e.g.* much larger electrodes). That means that processes have to be designed for manufacturability, *i.e.* higher precision, larger electrode areas, a deeper understanding of critical parameters, measurement of those parameters, larger process windows.

A unique case study revealing the impact of battery production advancements on the production equipment industry has been made by [12]. Basic principles of production, investment levels, and worldwide competition status have been indicated there. Mixing and coating have been identified as the most relevant process steps [12]. An even more detailed, very comprehensive overview on single process steps, process data, critical process steps, key technologies and investement levels for machines and equipment can be found in [13] for a Li-ion pouch cell, and in [14] for the assembly of a battery pack. A video, which has been produced by VDMA, also gives insights to all battery production steps and challenges for the machine makers [15].

Since this paper is aiming at the back-end of the process chain, we just refer to [12, 13] for details up to cell level.

Battery Module and Pack Assembly – Production Steps and Challenges

Battery module and pack assembly brings up a number of challenges: About 500 single parts have to be assembled in one battery system. There are *e.g.* 300 screw connections and 200–300 welding points to be set. The assembly of tubing and cover plates can only be achieved manually. A special requirement is workplace safety: the more cells are assembled, the higher the voltages that occur. Automation is possible for most of the process steps, but careful consideration if it pays off is needed. Investment into automation also depends on regional specialties. Battery production is still in an evolutionary phase (at least for high-power applications), *i.e.* requirements for automated production rapidly change.

A graphical overview of typical production steps based on pouch cells is given in Fig. 5.

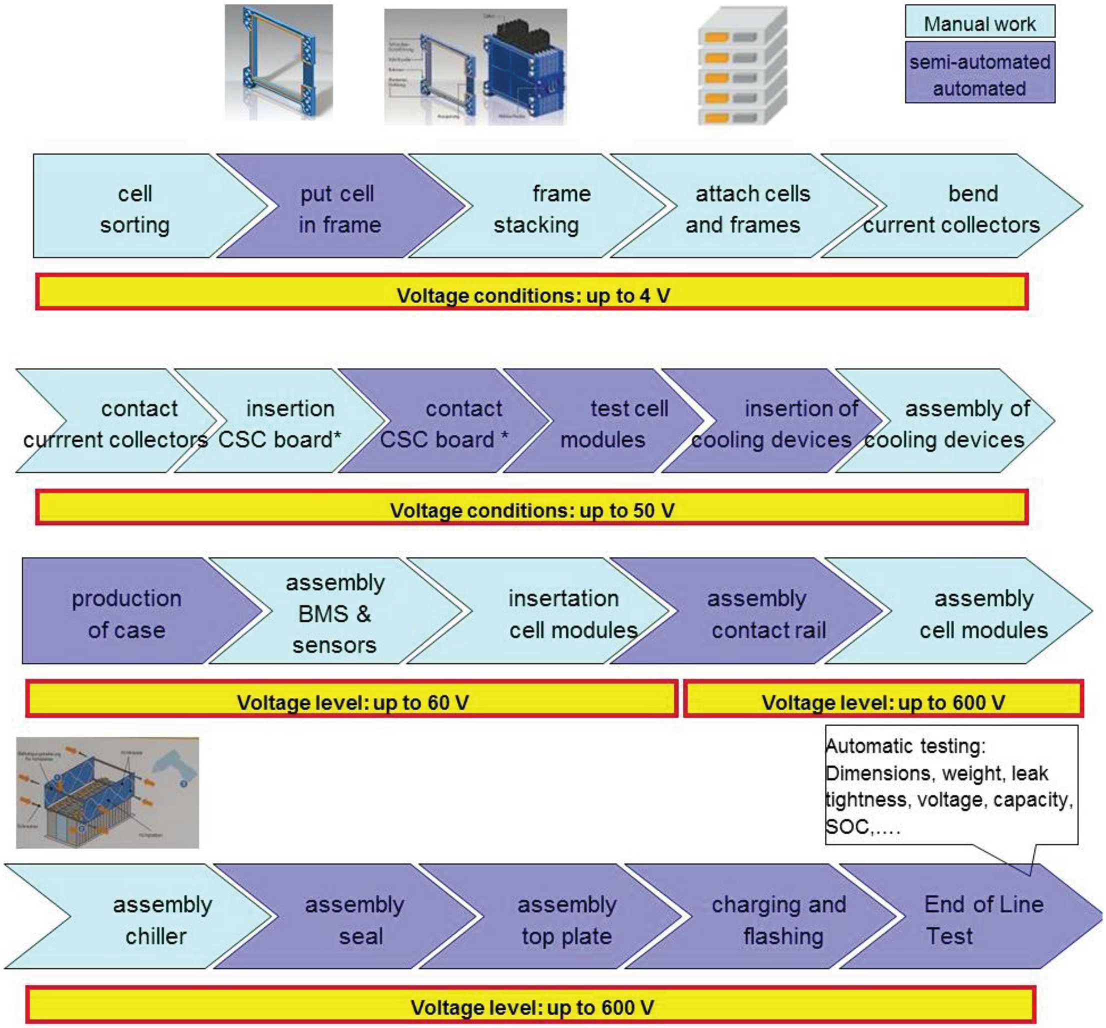

FIGURE 5. Typical module and pack assembly today: Process steps, automation level today, and voltage level for workplace safety. Example based on pouch cells. *Cell Supervision Circuit (CSC). Reprinted with permission of Klaus Schulz, Bosch Rexroth AG, and [16].

Although highly desireable for cost-effective production, a lot of production steps today still require manual handling, as indicated above. This is partly due to the precision required, partly a lack of measurement tecchnology, and partly an economical issue. On top of the mechanical automation, there is still a lack of automation on the information technology side, from data mining up to Manufacturing Execution Systems (MES). To set up this line integration, connecting single machines to highly automated turn-key lines must be a goal for the entire industry and poses a huge opportunity to the production equipment makers in the medium term [12].

Whereas clean room conditions and dry environment are an essential prerequisite in electrode and cell production, it is workplace safety in module and pack assembly that plays an important role for the production environment. Figure 5 clearly shows the high voltages up to 600 Volts that occur during all assembly steps.

TABLE 2. Overview of selected important process steps in module and pack assembly, critical factors and possible process solutions to cope with them. Compiled from [14, 16].

Process step and goal	Critical factors and challenges	Production solution
Cell sorting: Precise handling	• Pouch cells vary in form factor and surface, surface is not stiff • No alteration, puncture or contamination of surface, low contact pressure • Tight fit and precise positioning	• Complex gripping technology, *e.g.* large area vacuum gripper • Reliable and fast handling, stacking, supply of cells • Powerful logistics systemc
Contacting of current collectors	• Lowest possible thermal load for cell during process, fire hazard • Biggest possible surface area for weld	• Ultrasonic welding • Inspection of welded joint for full functionality by voltage test
Contacting of BMS and sensor system (thermal and voltage sensors, sensor system readout)	• Sensors are very damageable, needs very high precision • Danger of short-circiut by inaccurate positioning of sensors and printed circuit board	• Soldering, ultrasonic welding • High-precision handling • High degree of automation desireable
Assembly of housing, insertion and fixation of modules, attachment of module connections	• Screwing with high voltage on • Chip formation, danger of short • Heavy loads • Flexible cables are challenge for automated handling	• Sophisticated screwing technology, manual screwers with torque sensors, automation with screw jacks desireable • Self-tapping screws • Workplace safety
End-of-line test	• Uniform charging and testing of all cells • Leak tightness test involves high pressures, danger of burst	• Ripple-free DC technology with low voltage increase • Sophisticated Measurement and testing equipment • Burst disk required

Table 2 gives an overview of selected important process steps in module and pack assembly, critical factors and possible process solutions to cope with them. This clearly shows that backend processes are far from being trivial.

COST CONSIDERATIONS

Cost is the important driver for the success of electromobility or storage for renewable energy. Li-ion batteries for high-power applications are at a level of 750 US$/kWh today [18]. Price targets of around 250 €/kWh to be met in the 2020 timeframe have been set, *e.g.* by the German government, several roadmaps and independent studies [*e.g.* 12, 17, 18, 19]. Cell production accounts for up to 50 % of the cost of a battery today. Module and pack assembly still account for around 15 % of the total cost [12, 18]. This means that considerable cost reductions can be achieved through improved production technologies – mainly through higher productivity and yield. The leverage in this case is much bigger than in the raw materials part of the process chain through changes of the cell chemistry. At the same time, it is necessary to maintain the highest quality standards in order to avoid impairing battery lifetime and performance [12].

Only mass production will enable affordable solutions here. The investment in production facilities involves ca. 200 million € for a complete cell line, the investment into a battery packaging line is still at the level of 5 million € (basis: 10 million pouch cells with 20 Ah) [13, 14]. Details for the investments in the individual process steps can be found in [12, 13, 14]. With the market currently being slower than expected, manufacturers hesitate to heaviliy invest into new fabs. However, we believe that in the medium term the market will see an upturn, at least for stationary storage. Annual capital expenditure has been forecasted to almost 5 billion € in 2020 for traction batteries alone [12]. Investment into stationary storage will probably reach the same amount or higher.

Compared to the cost of production equipment for semiconductors and flat panel displays production facilities for battery cells are relatively inexpensive [12].

Best Practices from Semiconductors, Flat Panel Displays and Photovoltaics

The learning curves in production of semiconductors, flat panel displays and solar modules have shown significant cost degressions. In the semiconductor industry, this cost degression is also known as "Moore's Law". For DRAM, flat panel displays and photovoltaic cells a doubling of production capacity leads to a cost reduction of 40 %, 35 % and 20 %, respectively. Important contributions to this effect were made by the production equipment industry in fields such as glass and wafer manufacturing, coating technology, ovens, vacuum technology, handling, automation, laser technology, the lamination of substrates and the soldering of components.

Upscaling of pilot lines, timely introduction of alpha and beta tools following joint roadmaps and the close collaboration between manufacturers and their suppliers have made those industries very successful. Especially the roadmaps of the semiconductor industry have almost reached the status of a “self fulfilling prophecy”, which easens investment decisions. Success factors for the machine makers are to build consortia at an early stage that are able to offer entire turn-key lines and have the ability to offer technology packagings instead of just the bare machine. This way, the machine makers can become drivers of innovation. A good example for this is the very successful positioning of German photovoltaics machine makers on the world market.

Electronics, flat panel displays, photovoltaics and battery production employ comparable processes: They all start with chemical processing (*e.g.* electrode materials, ultra-pure silicon or glass), involve coating large areas with high accuracy (printing, PVD, CVD), require a high level of automation, utilise plastics (separators, laminates, encapsulation), take place in clean rooms and need investment in similar orders of magnitude. Labour costs play a minor role. Innovation cycles are short. Last but not least the products and therefore production are massively driven by cost.

Battery manufacturing can benefit greatly from the experience in those related industries. The experience of machine makers can pave the way to highly automated high-volume production of high-power batteries – and therefore make electromobility and energy storage more affordable.

Module Standardization as Additional Path to Decrease Cost

One of the key questions behind an investment into high volume battery manufacturing is to decide on a specific battery type. With the various chemistries, shapes and sizes in which Li-ion batteries appear on the market, standardization seems impossible. Small volumes in highly fragmented markets are hindering scaling, and thus the cost degression described above. On the module level there have been attempts to push for standardization, described in detail in [20].

The idea behind it: A modular, standard, general-purpose battery would tap potential synergies across a big variety of applications. Clearly defined external dimensions and interfaces would facilitate universal deployment of modules in many application areas. Different numbers of basic modules could be put together to supply the power needed by each application. The large cumulative number of units could thus cut costs significantly in many industries [20]. The study first looked into different market segments, including mobile machinery, stationary storage for residential PV, and recreational vehicles. In fact, mobile machinery has a broader installation base than batteries for electromnobility in the automotive sector. The segments analyzed in this study altogether account for the third-largest block of sales potential for all batteries, with a combined market volume of approximately 4 billion € in 2020 [20].

The concept for a modular standard battery involves standardization on the module level. It is always based on the same core module in order to realize economies of scale even for the most expensive components. The shape and chemistry of the battery cell are not standardized, to enable cells from both the automotive industry and other sectors (such as power tools and consumer markets) to be used. Thus, competition for powerful battery technologies, efficient production processes and innovative operator models will be further intensified as a result [20].

Despite less differentiation capability relative to competitors, possibly accompanied by thinner margins, battery manufacturers would clearly benefit from a broader spectrum of customers, lower bill of materials due to economies of scale, optimized set-up and cycle times, lower development costs and higher investment security [20]. The overall effect for battery integrators and end users is clearly an additional route to cost reduction.

SUMMARY

Although the front end production steps (up to cell level) have the highest impact on the characteristics and cost of a battery, back-end design and processes (packaging) significantly influence its shape and performance. The packaging adds important safety and intelligent control features. Especially Li-ion batteries would not be manageable without them.

Packaging is divided into cell, module and pack level. On cell level, cylindrical shapes have the longest history and are used for standard NiCd, NiMH, Li-Ion and even lead-acid chemistries. Modern handheld devices, as well as automotive traction applications have triggered prismatic and pouch types of cells.

High-volume mass production is already achieved for standard primary and secondary consumer-type batteries, as well as for lead-acid starter applications. However, improvements are still being made here, as cost pressure continues. For large-area, high-energy-type Li-ion batteries with big form factors there is a lot of room for optimization, worldwide. For a fab, a number of alternative processes and process parameters have to be chosen. Inspection is crucial. Furthermore, automation and line integration will greatly enhance yield, precision and workplace safety.

The experience made in the production of semiconductors, flat panel displays and photovoltaics can partly be adopted to battery production, since a lot of major characteristics for processes and ambient conditions are the same. Cost degression in those related industries has proven to be steep and scales with increase of production capacity. Machine makers can play a vital role in driving process technology and automation to the next level, using their experience from those industries.

However, the battery industry is stuck in small volumes in highly fragmented markets. This is hindering scaling, and thus the desired cost degression. On the module level there have been attempts to push for standardization, which would be a benefit to all players along the value chain.

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